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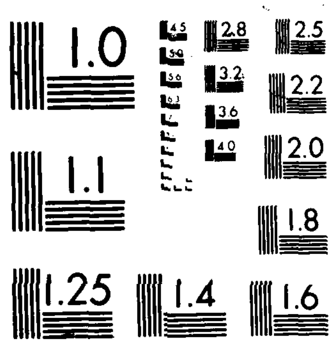

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US Army Corps
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Construction Engineering
Research Laboratory

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AD-A175 257

Survey of the State-of-the-Art Expert/Knowledge Based Systems in Civil Engineering

by
Simon S. Kim
Mary Lou Maher
Raymond E. Levitt
Martin F. Rooney
Thomas J. Siller
Stephen G. Richie

This survey assesses the current use and development of expert systems for approaching and solving civil engineering problems. The engineering disciplines discussed are: construction engineering and management, structural engineering, geotechnical and environmental engineering, and transportation engineering. Expert system applications for both operational and developmental uses are reviewed. Although artificial intelligence technology is relatively new for some disciplines, the survey results indicate a long-term commitment to research and development of expert systems for construction. Expert systems offer new and potentially valuable capabilities to support decisionmaking in civil engineering, with the goal of reducing costs.

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This survey assesses the current use and development of expert systems for approaching and solving Civil Engineering problems. The engineering disciplines discussed are: Construction Engineering and Management, Structural Engineering, Geotechnical and Environmental Engineering, and Transportation Engineering. Expert system applications for both operational and developmental uses are reviewed. Although artificial intelligence technology is relatively new for some disciplines, the survey results indicate a long term commitment to research and development of expert systems for construction. Expert systems offer new and potentially valuable capabilities to support decisionmaking in Civil Engineering, with the goal of reducing costs.

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FOREWORD

This survey was performed by the Committee on Expert Systems of the American Society of Civil Engineers' Technical Council on Computer Practices. The work was performed for the U.S. Army Construction Engineering Research Laboratory (USA-CERL), under Delivery Order Contract to Carnegie Mellon University; contract DACW88-85-D-007, delivery order #0002. This work was also supported by the Facilities Systems (FS) Division of USA-CERL under the In-Division Independent Research Program. The Contracting Officer Technical Representative was Dr. Simon S. Kim.

COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L.R. Shaffer is Technical Director.

CONTENTS

Chapter One
Introduction

Mary Lou Maher
Assistant Professor
Department of Civil Engineering
Carnegie Mellon University

Introduction

This report represents an effort to assess the current use and development of expert systems for civil engineering problems. The idea for such a report originated in the American Society of Civil Engineer's committee on Expert Systems. This report was prepared by members of this committee and sponsored by the US Army Corp of Engineers. The committee decided that an appropriate way to assess the current use and development of expert systems in civil engineering is to collect information through literature searches, surveys, and phone calls and to present them according to the area of civil engineering in which the expert systems are applied. The areas identified in this report are: Structural Engineering, Construction Engineering, Geotechnical and Environmental Engineering, and Transportation Engineering.

The literature search did not provide an abundance of information. The lack of published articles and reports reflects that the development of expert systems is still in the very early stages. The majority of the articles that were found came from conference proceedings; the largest number from the proceedings of the First Symposium on Expert Systems in Civil Engineering in Seattle in April 1986.

The survey was prepared by the authors of this report and was sent to universities and companies; primarily universities and companies in the United States, although some Canadian, European, and Australian representatives were sent surveys. The survey form is shown in Figure 1. A total of about 280 survey forms were mailed: about 200 to universities and colleges and about 80 to companies. The universities selected were those that have a graduate program in civil enginerering. The companies selected were those listed on the roster of the American Association for Artificial Intelligence. Of the 280 surveys sent, about 140, or 50 %, responded. The percentage of universities that responded was 60%, 120 out of 200 were returned. The percentage of companies that responded was 25%, only 20 out of 80 were returned. Overall, the response to the survey was good, and we are comfortable that the report represents a good estimate of the expert system applications to civil engineering problems in the United States in early 1986.

The results of the survey are shown in Table 1. The first column of Table 1 lists the locations that received a survey, the second column shows the response, the remaining columns indicate the name of the person involved in each area of civil engineering, as indicated in the survey response. The response to the survey is listed as

- **yes** if the location is actively involved in expert systems,
- **interested** if the location has identified people beginning to consider expert system development,
- **no *** if the location responded that either they are not interested or they are interested in, but not pursuing, expert system development, and
- **no** if the survey form was not returned.

The positive response to the survey is encouraging; 33 responses indicating expert system activity and 24 responses indicated interest in developing expert systems. The people and institutions that are **active** in developing expert systems are shown in Table 2. The distribution among the areas of civil engineering are

- 19 in Structural Engineering,
- 1 in Geotechnical Engineering,
- 10 in Construction Engineering,
- 6 in Transportation Engineering, and
- 11 in Environmental Engineering.

The people and institutions that are **interested** in developing expert systems are shown in Table 3. The distribution among the areas of civil engineering are

- 13 in Structural Engineering,
- 2 in Geotechnical Engineering,
- 6 in Construction Engineering,
- 6 in Transportation Engineering, and
- 9 in Environmental Engineering.

The largest group of people using or considering expert systems as a useful tool are the structural engineers, followed by environmental engineers.

This report is divided into four remaining chapters; each chapter addresses an area of civil engineering. Environmental and geotechnical engineering were combined because there was not enough activity in geotechnical engineering to constitute a separate chapter. Each chapter begins by

defining the activities or disciplines of the area of civil engineering being addressed, and provides some reasons why expert systems are being considered. Generally, expert systems are being considered when algorithmic approaches to automated problem solving are not appropriate or are extremely complex. Each chapter then presents expert system applications in two major categories: operational and developmental. The operational expert systems are further decomposed into commercial systems and prototypes. An interesting note is that there are commercial expert systems only in Structural Engineering and Construction Engineering. The developmental expert systems are further decomposed into those that are currently under development and those that are in the conceptual stage. Each author then provides a conclusion reflecting on the contents of the chapter and the implications for that area of civil engineering.

AMERICAN SOCIETY OF CIVIL ENGINEERS

TECHNICAL COUNCIL ON COMPUTER PRACTICES

Address reply to.

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Carnegie-Mellon Univ.
Schenley Park
Pittsburgh, PA 15213

SURVEY

1. Is your organization interested in using expert systems for civil engineering problems?

2. Has anyone in your organization engaged in development of expert systems for civil engineering problems? If so, who (title would be helpful)?

3. To what area(s) of civil engineering have expert system techniques been applied by the above persons (i.e., structures, geotechnical, construction, transportation, environmental)?

4. Please list any papers or articles (published or unpublished) that are related to your organization's work in expert systems in civil engineering (authors, title, publication title, location, year).

Figure 1.

(Use additional pages if necessary)

1	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
2							
3	Arizona State Univ	no*					
4	Auburn Univ	no*					
5	Bradley Univ	no					
6	Brigham Young Univ	no					
7	Bucknell Univ	no					
8	California Inst of Tech	no					
9	California Poly State Univ	interested				S. Hockaday	
10	California State Univ Fresno	no					
11	California State Univ Fullerton	no*					
12	California State Univ Long Beach	no					
13	California State Univ Los Angeles	no					
14	California State Univ Northridge	no					
15	California State Univ Sacremento	no*					
16	Carleton Univ	no					
17	Carnegie Mellon Univ	yes	S. Fenves	D. Rehak	C. Hendrickson	C. Hendrickson	
18	Case Western Reserve Univ	interested	interested				
19	Catholic Univ	no	no				
20	City Univ of New York	no*					
21	Clarkson Univ	no					
22	Clemson Univ	no					
23	Cleveland State Univ	no					
24	Colorado State Univ	no					
25	Columbia Univ	no					
26	Concordia Univ	no*					
27	Cooper Union	no					
28	Cornell Univ	no					
29	Dartmouth College	no*					
30	Drexel Univ	no					
31	Duke Univ	yes	M. Biswas				M. Medina
32	Ecole Poly de Montreal	interested	R. Tinawi			R. Chapleau	C. Marche
33	Florida Inter Univ	no*					
34	Florida Ints of Tech	no*					
35	George Washington Univ	no					

Table 1

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
36	Georgia Ints of Tech	yes			R. Kangari		R. Kangari
37	Howard Univ	no*					
38	Illinois Inst of Tech	interested			D. Arditi		
39	Indian Inst of Tech	no					
40	Iowa State Univ	no					
41	John Hopkins Univ	no*					
42	Kansas State Univ	yes					A. Mathews
43	Lehigh Univ	no					
44	Louisiana State Univ	interested	R. Avent				
45	Louisiana Tech Univ	no*					
46	Loyola Marymount Univ	no					
47	Manhattan College	no					
48	Marquette Univ	no					
49	Massachusetts Institute of Tech	no					
50	McGill Univ	no*					
51	McMaster Univ	no					
52	McNeese State Univ	no					
53	Menphis State Univ	no					
54	Michigan State Univ	no					
55	Midwest College	no*					
56	Mighigan Tech Univ	no*					
57	Mississippi State Univ	no					
58	Montana State Univ	no*					
59	New Jersey Inst of Tech	no					
60	New Mexico State Univ	interested				T. Ward	T. Ward
61	New York Poly Inst	no					
62	North Carolina A&T State Univ	no*					
63	North Caroline State Univ	yes	W. Rasdorf				A. Chao
64	North Dakota State Univ	no					
65	Northeastern Univ	no					
66	Northwestern Univ	no					
67	Ohio Univ	no*					
68	Ohio Sate Univ	yes	H. Adeli				
69	Oklahoma State Univ	no					

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
70	Old Dominion Univ	no*					
71	Oregon State Univ	no					
72	Osaka Univ	yes	S. Fukuda				
73	Penn State Univ	interested			H. Thomas		
74	Poly Inst of New York	interested	M. Karamouz				A. Tallin
75	Portland State Univ	no*					
76	Princeton Univ	no					
77	Purdue Univ	yes	J. Yao			J. Fricker	M. Houck
78	Queens Univ at Kingston	no*					
79	Rensselaer Poly Inst	yes	K. Law				T. Zimmie
80	Rice Univ	no*					
81	Rose-Hulman Inst of Tech	no*					
82	Rutgers Univ	no					
83	San Diego State Univ	no					
84	San Jose State Univ	interested	T. Zsutty				
85	South Dakota School of Mines	no					
86	South Dakota State Univ	no*					
87	Southern Illinois Univ Carbondale	no					
88	Southern Illinois Univ Edwardsville	no					
89	Southern Methodist Univ	no					
90	Stanford Univ	yes	H. Shah		R. Levitt		
91	Stevens Inst of Tech	no					
92	SUNY at Buffalo	no*					
93	Swiss Federal Inst Tech	yes			H. Knoepfel		
94	Syracuse Univ	no					
95	Technical Univ of Nova Scotia	no*					
96	Tennessee Tech Univ	no					
97	Texas A&I Univ	no					
98	Texas A&M Univ	no					
99	Texas Tech Univ	no*					
100	Tufts Univ	yes					L. Brown
101	Tulane Univ	no					
102	Univ of California Berkeley	yes			T. Chang	G. Gosling	
103	Univ of California Davis	no					

Table 1, continued

	Institution	Response	Structural	Geotechnical	Construction	Transportation	Environmental
104	Univ of California Los Angeles	no					
105	Univ of Cape Town	no					
106	Univ of Central Florida	no*					
107	Univ of Cincinatti	no*					
108	Univ of Colorado Boulder	yes	J. Dickmann		V. Sorima		
109	Univ of Colorado Denver	no*					
110	Univ of Connecticut	no*					
111	Univ of Dayton	no					
112	Univ of Delaware	no					
113	Univ of Detroit	no					
114	Univ of Evansville	no*					
115	Univ of Florida	no					
116	Univ of Hawaii	no*					
117	Univ of Houston	no					
118	Univ of Idaho	no*					
119	Univ of Illinois Urbana	yes			M. O'Connor		
120	Univ of Kansas	no					
121	Univ of Kentucky	no*					
122	Univ of Louisville	yes				L. Cohn	
123	Univ of Lowell	no*					
124	Univ of Maine	no					
125	Univ of Manitoba	no					
126	Univ of Maryland	no					
127	Univ of Massachusetts	yes	C. Dym				
128	Univ of Michigan	interested		P. Ioannou			
129	Univ of Minnesota	no					
130	Univ of Misouri Columbia	interested			N. Benjamin		
131	Univ of Misouri Rolla	no					
132	Univ of Mississippi	no					
133	Univ of Nebraska	interested					I. Bogardi
134	Univ of Nevada Reno	no*					
135	Univ of New Brunswick	no					
136	Univ of New Hampshire	no*					
137	Univ of New Mexico	interested					

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
138	Univ of New Orleans	interested					A. Hannoura
139	Univ of North Carolina	no*					
140	Univ of North Dakota	no					
141	Univ of Notre Dame	no					
142	Univ of Oklahoma	no*					
143	Univ of Ottawa	no					
144	Univ of Pennsylvania	interested	J. Keenan				J. Lepore
145	Univ of Pittsburgh	interested	J. Abrahms				
146	Univ of Portland	interested	interested	interested		interested	interested
147	Univ of Puerto Rico	interested	C. Pasquera				
148	Univ of Reading	yes			C. Gray		
149	Univ of Regina	no*					
150	Univ of Rhode Island	no*					
151	Univ of Saskatchewan	yes				G. Sparks	
152	Univ of South Carolina	no*					
153	Univ of South Florida	no*					
154	Univ of Southern California	no*					
155	Univ of Southwestern Louisiana	no					
156	Univ of Sydney	yes	J. Gero				
157	Univ of Technology Loughborough	yes			R. Allwood		
158	Univ of Tennessee	no					
159	Univ of Texas Arlington	no					
160	Univ of Texas Austin	yes			D. Ashley		
161	Univ of Texas El Paso	no					
162	Univ of Toledo	interested					A. Jennings
163	Univ of Toronto	no					
164	Univ of Utah	no					
165	Univ of Vermont	no					
166	Univ of Virginia	interested				M. Demetsky	
167	Univ of Washington	no					
168	Univ of Waterloo	no					
169	Univ of Western Ontario	no*					
170	Univ of Windsor	no*					
171	Univ of Wisconsin	no					

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
172	Univ of Wyoming	no					
173	Universite de Moncton	no					
174	Universite de Sherbrooke	no					
175	Universite Laval	no					
176	University of Akron	no					
177	University of Alabam Birmingham	no*					
178	University of Alabama	no*					
179	University of Alaska Anchorage	no*					
180	University of Alaska Fairbanks	interested					interested
181	University of Alberta	no*					
182	University of Arizona	no*					
183	University of Arkansas	no*					
184	University of British Columbia	yes					S. Russell
185	University of Calgary	no*					
186	University of Illinois Chicago	no*					
187	University of Iowa	no*					
188	University of Miami	interested	S. Malasri		s. Malasri		
189	Utah State Univ	yes					W. Grenney
190	Vanderbilt Univ	yes	P. Basu			W. Bowlby	
191	Villanova Univ	interested	P. Hoffman				
192	Virginia Poly Inst	no*					
193	Washington State Univ	yes	H. Sorensen				
194	Washington Univ	no*					
195	Wayne State Univ	yes	T. Arciszewski				
196	West Virginia College	no*					
197	West Virginia Inst Tech	no*					
198	West Virginia Univ	interested	H. GangaRao			R. Eck	
199	Widener Univ	no*					
200	Worcester Poly Inst	interested	G. Salazar		P. Jayachandran		
201	Youngstown State Univ	no					
202		no					
203	Air Force Weapons Lab	yes	T. Ross				
204	Air Products & Chemicals Inc	no*					
205	Alan Campbell and Associates	no					

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
206	Alcoa Technical Center	no					
207	Amoco Production Co	no*					
208	Arthur Anderson & Co	no*					
209	Arthur D Litle	no					
210	AVCO Lycoming	no					
211	Bechtel	no					
212	Bendix Corp	no					
213	Black & Decker	no					
214	Bolt Beranek and Newman	no					
215	CADAM Inc	no					
216	Calcomp 2411	no					
217	Camplin Petroleum Co	no*					
218	Caterpillar Tractor Co	no					
219	Combustion Engineering	no					
220	CSIRO Australia	yes	R. Sharpe				J. Thompson
221	Deere and Co	no					
222	Defense Mapping Agency	no					
223	Dept of Ship and Marine Tech	no					
224	Digital Equipment Corp	no					
225	Electric Power Research Inst	no					
226	Environmental Tech Assoc	no					
227	EPA WERL	yes					L. Rossman
228	ES&G Idaho	no					
229	Exxon Chemical	no*					
230	Exxon Production Research	no*					
231	Exploration Logging Inc	no					
232	FMC Corp	no*					
233	Ford Motor Co	no					
234	General Electric	no					
235	Geodynamics Inc	no					
236	Gulf Canada Ltd	no					
237	Hartford Steam Boiler	no					
238	Herculies Inc	no					
239	Inst fro Mgmt of Innov and Tech	yes			H. Bjornsson		

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
240	Johnson Controls Inc	no*					
241	Lynchburg Research Center	no					
242	Martin Marietta Energy Systems	no					
243	Mitre Corp	no					
244	Mobil R&D	no					
245	Monsanto AG Research	no					
246	Motor-Columbus Ltd	interested			B. Raschle		
247	National Bureau of Standards	no					
248	Naval Ocean R&D	no					
249	Naval Ocean Systems Center	no*					
250	Norhtwest Industries Inc	no					
251	Oceanic Division Westinghouse	no					
252	Owens-Corning Fiberglass	no					
253	Phillips Petroleum Co	no					
254	Potomac Systems Engineering	no					
255	RFT Associates	no					
256	Rockwell International	no					
257	Rockwell Science Center	no					
258	Santa Fe Drilling Corp	no					
259	Schlumberger Well Service	no					
260	Schlumberger-Doll Research	no*					
261	Science Magazine	no					
262	Shell Development	no					
263	Skidmore Owings Merrill	yes	M. Evans				
264	Sohio Petroleum Co	no					
265	South Florida Water Mgmt District	no					
266	Standard Oil Co	no					
267	Stone and Webster	yes	G. Finn				
268	Swedish Industrial Dev Corp	no					
269	Texaco Inc	no*					
270	Union Carbide Corp	no					
271	US Army Soldier Support Center	no*					
272	US Environmental Protection Agency	no					
273	US Geological Survey	no					

Table 1, continued

	Location	Response	Structural	Geotechnical	Construction	Transportation	Environmental
274	USCG R&D Center	no					
275	Water Reactor Division Westinghouse	no					
276	Weidlinger Associates	yes	F. Wong				
277	Western Geophysical	no					
278	Westinghouse	no*					
279	Westinghouse ESD	no					
280	Westinghouse R&D	no*					
281	Westinghouse Hunt Valley	no*					
282	Weyerhauser Co	no					

Table 1, continued

Structural	Geotechnical	Construction	Transportation	Environmental	Location
S. Fenves	D. Rehak	C. Hendrickson	C. Hendrickson		Carnegie Mellon Univ
M. Biswas				M. Medina	Duke Univ
		R. Kangari		R. Kangari	Georgia Ints of Tech
				A. Mathews	Kansas State Univ
W. Rasdorf				A. Chao	North Caroline State Univ
H. Adeli					Ohio Sate Univ
S. Fukuda					Osaka Univ
J. Yao			J. Fricker	M. Houck	Purdue Univ
K. Law				T. Zimmie	Rensselaer Poly Inst
H. Shah		R. Levitt			Stanford Univ
		H. Knoepfel			Swiss Federal Inst Tech
				L. Brown	Tufts Univ
		T. Chang	G. Gosling		Univ of California Berkeley
J. Dickmann		V. Sorima			Univ of Colorado Boulder
		M. O'Connor			Univ of Illinois Urbana
			L. Cohn		*Univ of Louisville*
C. Dym					Univ of Massachusetts
		C. Gray			Univ of Reading
			G. Sparks		Univ of Saskatchewan
J. Gero					Univ of Sydney
		R. Allwood			Univ of Technology Loughborough
		D. Ashley			Univ of Texas Austin
				S. Russell	University of British Columbia
				W. Grenney	Utah State Univ
P. Basu			W. Bowlby		Vanderbilt Univ
H. Sorensen					Washington State Univ
T. Arciszewski					Wayne State Univ
T. Ross					Air Force Weapons Lab
R. Sharpe				J. Thompson	CSIRO Australia
				L. Rossman	EPA WERL
		H. Bjornsson			Inst fro Mgmt of Innov and Tech
M. Evans					Skidmore Owings Merrill
G. Finn					Stone and Webster
F. Wong					Weidlinger Ass

Table 2

Structural	Geotechnical	Construction	Transportation	Environmental	Location		
			S. Hockaday		California Poly State Univ		
interested					Case Western Reserve Univ		
R. Tinawi			R. Chapleau	C. Marche	Ecole Poly de Montreal		
		D. Arditi			Illinois Inst of Tech		
R. Avent					Louisiana State Univ		
			T. Ward	T. Ward	New Mexico State Univ		
		H. Thomas			Penn State Univ		
M. Karamouz				A. Tallin	Poly Inst of New York		
T. Zsutty					San Jose State Univ		
	P. Ioannou				Univ of Michigan		
		N. Benjamin			Univ of Missouri Columbia		
				I. Bogardi	Univ of Nebraska		
					Univ of New Mexico		
				A. Hannoura	Univ of New Orleans		
J. Keenan				J. Lepore	Univ of Pennsylvania		
J. Abrahms					Univ of Pittsburgh		
interested	interested		interested	interested	Univ of Portland		
C. Pasquera					Univ of Puerto Rico		
				A. Jennings	Univ of Toledo		
			M. Demetsky		Univ of Virginia		
				interested	University of Alaska Fairbanks		
S. Malasri		s. Malasri			University of Miami		
P. Hoffman					Villanova Univ		
H. GangaRao			R. Eck		West Virginia Univ		
G. Salazar		P. Jayachandran			Worcester Poly Inst		
		B. Raschle			Motor-Columbus Ltd		

Table 3

Chapter Two
Expert Systems in Construction

Raymond E. Levitt
Department of Civil Engineering
Stanford University

Expert Systems in Construction: State of the Art

Raymond E. Levitt
Department of Civil Engineering
Stanford University

1. Introduction

The term *Construction* in this chapter title is intended to cover the field generally referred to as *Construction Engineering and Management*. This is a broad area of civil engineering practice which includes: (1) planning and engineering of the temporary facilities for construction sites; (2) management of the construction process; and (3) rehabilitation, repair and maintenance of engineered facilities where the traditionally distinct design and construction roles of participants have become merged. The broad scope of this field, combined with the empirical nature of many facets of construction engineering and management practice, have led to a significant amount of expert system activity in this domain.

This chapter seeks to present a reasonably complete snapshot of the state of the art of expert systems in *Construction Engineering and Management* in mid-1986. Library and on-line searches of engineering, computer and business publications have been carried out; the civil engineering departments of all USA universities and those foreign universities known to be working in this area have been surveyed; and we have attempted to contact private firms and government agencies that we suspected might be engaged in development of expert systems applications in the area of *Construction Engineering and Management*. However, we have undoubtedly missed some expert system applications, especially those in the early stages of development and those outside the USA. This chapter should, therefore, be considered as a representative, but not exhaustive, catalogue and discussion of ongoing expert system work in construction at this time.

We start by defining the field of *Construction Engineering and Management* in more detail to illustrate the types of decisions that might be candidates for expert systems in this domain. Next we consider why expert systems might profitably be applied to problem solving in this domain, and find strong motivations for the use of expert systems in this area of civil engineering practice. The bulk of the chapter is devoted to descriptions of a series of applications, ranging from *operational* systems (in routine use by persons other than their developers) to research projects still in the conceptual stages, in order to give the reader a sense both of where the state of the art currently is, and of where it might be headed over the next few years. In the conclusion, we summarize the work described in the chapter and speculate about the directions of future research and development efforts.

1.1 WHAT IS CONSTRUCTION ENGINEERING AND MANAGEMENT?

We will divide this field up into three major areas: engineering of temprary facilities for construction; management of the construction process; and rehabilitation, repair and maintenance of engineered facilities.

1.1.1 Construction Engineering

The first subfield of *Construction Engineering and Management* involves all of the planning and design decisions related to the equipment and physical facilities involved in the construction process. In US practice, these decisions are typically carried out by different individuals than those who design the permanent facility. This represents the *Construction Engineering* portion of *Construction Engineering and Management.* Decision-making tasks associated with this area which might be candidates for formalization via expert systems techniques are listed here.

1.1.1.1 Design of Construction Methods

Construction methods to be followed are almost always left to the discretion of the contractor in US practice. There are few formal techniques available for selecting construction methods; experience plays a large role in performing this task.

Experience-based decisions to be made in this area include: configuration of crews; selection of equipment types, sizes and combinations; design of transportation facilities (roads, railways, conveyors, cableways, cranes, hoists) for moving personnel, materials and equipment around the jobsite; and approaches to prefabrication or modularization of components for the permanent facility, including locating construction joints in slabs or walls.

1.1.1.2 Concrete as a Manufactured Material

The details of manufacturing and placing concrete in a permanent facility are almost always left to the contractor. Decisions to be made here include: mix design, both to meet final perfomance specifications and to accommodate the method of placement selected; design of crushers, batch plant, and transportation systems; and stuctural and functional design of formwork and falsework.

1.1.1.3 Geotechnical Engineering for Construction

Although deep excavations are usually designed by a project's geotechnical engineer, the design of smaller excavations, pads for temporary facilities, access roads, tunnel support or coffer dams may involve geotechnical engineering decisions on the part of the contractor.

1.1.1.4 Constructability Evaluation

The evaluation and critique of engineering designs in terms of ease and cost of construction has been termed *constructability evaluation.* This covers a range of different problems ranging from strategic issues such as defining the boundaries of bid packages to operational issues such as optimizing connection details.

1.1.1.5 Site Layout

The location of temporary facilities such as material lay down areas, fabrication shops and office trailers on a construction site can have significant impacts on travel time, worker productivity and safety. This function is usually carried out by a contractor's most experienced site managers.

1.1.1.6 Surveying

Surveying is associated with the precise location of permanent facilities, and is often considered a separate discipline from civil engineering; however, we have chosen to include it within the scope of this chapter. Although surveying calculations are relatively straightforward, aspects of setup and performance of surveying in the field involve more judgemental decisions by experienced surveyors.

1.1.2 Construction Management

In contrast to *Construction Engineering*, which involves the planning and design of **physical** aspects of the construction process, *Construction Management* consists of managing the **administrative**, **legal**, **financial** and **behavioral** aspects of construction.

1.1.2.1 Project Planning, Scheduling and Control

This function is now widely supported by the use of network-based project scheduling techniques for analysis, and by database management systems for reporting. Decision-making tasks in this area that could be candidates for expert systems include: developing time and cost estimates of construction tasks, particularly in the early stages of project planning; allocating constrained resources to activities; monitoring time and resource consumption; diagnosing reasons for cost, time or resource overruns, forecasting durations and costs of remaining activities on projects; and developing remedial actions for project control.

1.1.2.2 Contract Management

The processes of developing contracting approaches and of administering contracts throughout the life of projects involve several kinds of expert decision making. Representative decisions in this area involve: selecting an overall contracting approach or strategy; selecting contract clauses to incorporate; identifying and refining project financing or insurance options; prequalifying or selecting prospective contractors or designers; evaluating progress payments; evaluating potential claims or litigation situations; quality assurance; and project organization design.

1.1.2.3 Construction Company Management

Several areas of construction company management are being included under our definition of *Construction Management*. These include: marketing strategy decisions such as whether to submit a bid for a project or how much to mark it up; personnel management decisions; company organization design; financial planning, construction equipment policy decisions; and safety management.

1.1.3 Rehabilitation, Repair and Maintenance

In this area, the separation between designers and contractors that exists for most new construction has become blurred in practice. The individuals who diagnose deficiencies and recommend remedies for rehabilitation, repair and maintenance of capital facilities are often also involved with overseeing or conducting the construction work. Many of the firms who carry out this type of work for industrial or commercial clients, also perform new construction. Moreover, we learned that several operational expert systems have been developed by engineering-construction firms in this area and others are under development. Consequently, we have included them in this chapter.

1.2 REASONS FOR USING EXPERT SYSTEMS IN CONSTRUCTION

Our survey found substantial research and development activity in the application of expert systems to decision-making in construction. We can see several reasons why this area of civil engineering might be a good candidate for expert systems.

1.2.1 Construction is an Experience-Based Industry

Construction engineering is far less formalized than the engineering of permanent facilities. Codes or regulations impose far fewer guidelines or restrictions for the design of coffer dams, cableways or conveyor belts than they do for high rise buildings or highway pavements. Moreover, the materials employed for temporary facilities -- e.g., soil, plywood, or recycled sheet metal -- tend to be much less homogeneous than those used in the construction of permanent facilities. Consequently, expertise about how to engineer such facilities tend to be based upon individual experience, and passed down to younger engineers by "apprenticeship" with experienced couterparts.

Perhaps even more importantly, the construction process is impacted by a great deal of variance resulting from both its one-off production technology, and from external influences such as weather, regulatory agencies and the like. For this reason, structured approaches to decision making are difficult to develop. Decision rules in construction management manuals -- where these exist -- tend to look very much like the "*IF ...condition.... THEN ...action...* " rules that are employed to represent knowledge in rule-based expert systems.

There are formal techniques available from operations research or other disciplines which could potentially help in analyzing many of the types of problems that we have outlined above. For example, linear optimization has been proposed as a technique to optimize construction site layout. However, since the processes involved in construction involve far less repetition than is true for manufacturing processes, and since the construction processes are so much influenced by site- and time-specific events, the acquisition of meaningful data to use in such formal optimization models is extremely difficult and costly to obtain. Researchers are attempting to address this shortcoming through development of techniques for automated data capture on construction sites [Paulson85]. However, the present shortage of reliable data on, e.g., cycle time distributions of earthmoving equipment, greatly limits the applicability of formal optimization methods in construction at the present time.

All of these factors tend to promote the value of knowledge based on experience over knowledge of formal decision-making methods in the construction industry, as many a young engineering graduate has discovered.

1.2.2 Construction Decisions Must be Made Fast

Decisions taken in a design office can sometimes involve significant pressures for speedy resolution. However, decisions to be made on a construction site, when large numbers of workers and machines can be temporarily idled, involve far more immediate and visible pressure for speedy resolution. The construction adages, *"Any decision is better than no decision."* or *"Ask forgiveness, not permission,"* spring from this environment. The ability to make decisions on the spot, based upon wholistic comparisons with analogies from past experience, rather than upon a detailed analysis of all the elements of a given situation, is the hallmark of a successful construction executive.

Expert systems can be used to capture an experienced manager's knowledge about the key attributes of a given situation that should be used to select valid analogies from prior experience and to recommend suitable action plans.

1.2.3 Construction Decisions Involve Managerial Issues

Managerial issues, by their nature, involve variables that are more qualitative and subjective than the variables involved in technical issues. The engineers who design permanent facilities must also consider economic aspects of their technical decisions, but the immediacy and intertwining of economic and managerial aspects of decision-making in construction is much greater.

This intertwining of managerial issues with most decisions calls for less algorithmic solution methods, such as decision-making by analogy or the use of rules of thumb -- styles of decision-making that expert systems were developed to model.

1.2.4 Construction Automation Needs Smart Robots

Researchers who have studied construction automation have concluded that fixed, programmable robots such as those used in factory automation will have limited application is construction settings [Rehak85] [Paulson85]. These researchers have concluded that construction robots require adaptive planning capabilities to respond to changes in the dimensions and site conditions of a construction project over time. We have reported one expert system research effort in progress to begin to understand the issues involved in developing more autonomous construction equipment than the laser-controlled or tele-operated "robots" currently in use (See **2.4.1.2**). We believe that expert systems may turn out to be valuable as programming languages in developing knowledge-based planning capabilities for construction robots.

For all of these reasons, we see expert systems as offering valuable new capabilities to provide decision support for *Construction Engineering and Management* tasks which have hitherto not been formalized. The many, wide-ranging applications described in the following sections provide strong evidence for this claim.

2. Expert System Applications in Construction

Our survey found expert system applications ranging from systems which are in routine use by persons other than their developers to ideas for expert system development which are currently little more than a gleam in a scientist's or manager's eye. We have

chosen to report these application in four categories. The first will deal with what we term *Operational Expert Systems*. We define these to be systems which have proceeded through a prototype stage, have undergone significant validation and refinement, and are currently in use by persons other than their developers on a routine basis.

The largest number of systems in our survey are one step away from being operational. We call them *Operational Prototypes*. These systems have been prototyped and run, but are still in the validation and refinement stage. We describe them second.

Next we report two kinds of expert system applications that are earlier along in their development. If a system has resulted in a first working prototype, we have classified it as a *Developmental Expert System*. If an idea for an expert system has been worked out in some detail, and programming or knowledge acquisition is under way, we have referred to it as a *Conceptual Stage Expert System*. A number of systems of this type are described last to give an indication of future directions in this field.

2.1 OPERATIONAL EXPERT SYSTEMS

The following systems are currently in routine use by organizations in the construction industry. They represent those expert systems that have entered civil engineering practice in the field of *Construction Engineering and Management*.

2.1.1 Operational Expert Systems in Construction Engineering

We list one operational expert system in the category of *Construction Engineering*.

2.1.1.1 Field Diagnosis of Welding Defects

General Description: This system allows field personnel, welders, supervisors or quality control personnel to determine likely causes of weld defects. The program takes into account different welding procedures, code requirements, site conditions, and observations. The program enables more rapid repair of welding defects, thus reducing rework costs.

Methodology: Users of this program are asked to select the type of weld in question and describe the conditions of the failed weld by answering simple English language questions. The program then reasons through a possible list of causes and determines a reason for the failed weld. An example of a response given is "slag was allowed to build up on the first pass."

Present Status: Parts of the program are implemented, while other modules are still under development. This system, although currently available on-line, is thus less far along in its development than the other SWEC systems described in this chapter. The weld diagnosis program is written using the expert system shell EXSYS for use on an IBM-PC class of microcomputer. Users can access the program by modem from Stone and Webster Engineering Corporation. It is one of a family of similar systems offered by SWEC, accessible by modem using an IBM-PC class of computer. (See also **2.1.3.1** and **2.1.3.2**). About 400 of SWEC's clients have copies of the software and passwords needed to access this and two other expert systems. Users are assessed a charge based on connect time to the SWEC computer in Boston, MA.

The present configuration for on-line access by users has the user's PC act as a terminal to SWEC's IBM PC AT, hosting both the expert system shell and the knowledge bases. Communication through the modem makes the program run rather slowly, especially with the large quantity of text which this system must send to the user's screen. An alternative mode of operation would be for SWEC to have the expert system shell resident on licenced users' computers, and to assess users a charge for downloading the latest version of the knowledge base each time it was run.

Reference: [Finn86]

2.1.2 Operational Expert Systems in Construction Management

Our survey found two operational expert systems in the category of *Construction Management*. They are described in this section.

2.1.2.1 Know-How Transfer Method

General Description: Changes in the world economy in the 1970's spawned many large construction projects in foreign countries, especially in the Middle East. These large construction projects faced the multitude of problems associated with working within a different culture, with different social, cultural, and religious values. There was a corresponding increase in the risks associated with building in these countries, and an increase in research to mitigate these risks. The expert system discussed here was designed to help project managers with risk management at the project execution stage, and its main focus is in identifying risks in advance.

Methodology: The primary new feature of this expert system has been the development of the "know-how" transfer method of acquiring knowledge for the system to use. Know-how is described as the multidisciplinary knowledge needed by the project manager in the different areas of managerial, technical, economic, financial, social/science, and legal/political skills. The system stores the risk know-how onto a standard work package matrix. Know-how then becomes a function of the construction activity, and the object involved in the construction. The standard work package matrix consists of columns indicating activities, and rows indicating objects. Each job in the project is a function of the activity and the object. Know-how acquired on a project is also related to an activity and an object, and is placed onto the grid. This "know-how grid" is then mapped onto the standard work package matrix so the knowledge may be related to the work packages, and thus organizes itself as a suitable index of knowledge.

The computer system can provide information in several different ways. For instance, the input data may be a work package, and the output data could be risk-reducing strategies that should be followed for that activity. Another example would be to input a risk, and receive as output the risk factors involved, as well as other possible risks resulting from the original risk factors.

It is difficult to tell from published material whether the risk management system is, strictly speaking, an expert system according to our criteria in Chapter 1. Although the authors describe it as an expert system, the details of how it is programmed are not described in any of the materials provided to us.

Present Status: This knowledge-based risk management system for large project execution was developed at the Advanced Research Laboratory, Hitachi, Ltd., Japan, and is currently being used at Hitachi, Ltd. on a Hitachi Computer (HITAC M-200).

Reference: [Niwa82]

2.1.2.2 SAFEQUAL: Evaluating a Contractor's Expected Safety Performance

General Description: *The Business Roundtable's* study of the user's role in construction safety determined that construction buyers should prequalify contractors based, in part, on their expected safety performance. This could be evaluated by examining both past accident experience and present safety management practices of construction firms. A study commissioned by *The Business Roundtable* produced a first pass at a questionnaire for this purpose [Levitt81]. The questionnaire was subsequently reproduced in the "A-3" summary report of the project produced by *The Business Roundtable* and distributed to over 100,000 readers [BRT82].

As users began to try to evaluate contractors using the questionnaire, they found that some areas of the evaluation (e.g., interpreting experience modification ratings of joint venture firms) seemed to require levels of expertise or judgement beyond what their purchasing or facility engineering staff possessed. This provided the impetus to produce SAFEQUAL, an expert system to assist users in carrying out dependable and consistent contractor safety evaluations.

Methodology: SAFEQUAL was developed as a decision model in *The Deciding Factor*™ expert system shell which runs on IBM PC and compatible personal computers. Construction buyers send out a two page questionnaire with their other prequalification materials to prospective contractors. SAFEQUAL uses several type of Boolean logic to combine the contractor's responses to these questions into degrees of belief in subgoals, e.g., *This contractor has an acceptable insurance record*, and finally into a top level hypothesis, *This contractor's expected safety performance is acceptable.* Out-of-range responses on specified questions, e.g., those dealing with past insurance losses, will trigger elimination of a contractor from eligibility to bid or propose on the project, by means of *The Deciding Factor*'s conditional logic. These "kill" ranges can conveniently be adjusted using *The Deciding Factor* editor.

SAFEQUAL is a simple expert system -- much like an intelligent checklist, combined with a spreadsheet -- with the capability to instruct a novice user as needed in interpreting contractor responses to the questionnaire, or to justify its evaluation of a contractor's expected safety performance. Moreover, the ease of use of *The Deciding Factor* as an expert system delivery vehicle means that users with no prior computer experience have been able use this system with just a one page instruction sheet.

Present Status: SAFEQUAL underwent field testing in the spring of 1986 resulting in some minor refinements. It is being distributed as an off-the-shelf product, or customized for individual construction buyers' preferences, by *Building Knowledge Systems, Inc.* of Stanford California.

References: [BRT82] [Levitt81]

2.1.3 Operational Expert Systems in Maintenance

2.1.3.1 PUMP PRO^{TM}: Centrifugal Pump Failure Diagnosis

General Description: Most facilities constructed today have numerous pumps in place which must be started and tested as part of project completion. Correction of failures often necessitates the use of expensive and time consuming consultants. Although this program is principally designed to diagnose pump failures at operating locations such as power and process plants, PUMP PRO can be used to diagnose pump problems by on-site personnel during the start-up phase. The intent of the program is to allow mechanics, technicians and millwrights to avail themselves of expert knowledge in this domain.

Methodology: The program is written in MAIDS, Microcomputer Atificial Intelligence Diagnostic Service, a proprietary software program developed at *Stone and Webster Engineering Corporation* (SWEC). This inference mechanism is a forward-chaining, rule-based program that uses a subset of the English language for representing the rules. The program has two modules, a rule compiler and an execution module.

Diagnosis by PUMP PRO is accomplished in four phases: (1) identification of the symptoms, (2) identification of the causes, (3) provision of tutorials, and (4) suggestion of remedies. PUMP PRO dignoses problems by means of twenty-two possible symptom classes and a summarized pump history. It allows input of multiple symptoms and provides seven extensive tutorials and many minor tutorials in the problem identification rules.

Present Status: **PUMP PRO** is an operating system containing several hundred rules. It is accessed by users via modem as described in **2.1.1.1.**

Reference: [Finn86]

2.1.3.2 Vibration Analysis Interpretation

General Description: The process of diagnosing problems in rotating machinery, as with any diagnosis, is dependent, to a large extent, on the data used to make a diagnosis, and the expertise of the diagnostician. Vibration monitoring and measuring is a well practiced art in routine maintenance and it has been found that there are experts in this field who can identify causes of vibration after examination of very few data. This program was developed in order to improve the performance of engineers who are assigned the task of vibration diagnosis.

Methodology: This program, developed by Stone and Webster Engineering Corporation (SWEC) using the expert system shell EXSYS, is designed to run on standard, IBM-PC class microcomputers. The program operates in an interactive question/answer format, obtaining most of its required information from the user, or from the output of its own frequency analysis software. The system is rule-based, containing over one hundred rules. It is able to diagnose eighteen separate causes of vibration. The program presents in ranked order, the possible cause of the vibration and gives fairly detailed explanations of each.

Present Status: This program is available for use by clients of SWEC by use of a telephone modem hookup. (See **2.1.1** for a discussion of the strengths and weaknesses of this delivery system.)

Reference: [Finn86]

2.2 OPERATIONAL PROTOTYPE EXPERT SYSTEMS

The following systems are prototypes of operational systems. They have undergone at least one cycle of validation or testing and refinement, and are moving towards operational status.

2.2.1 Operational Prototype Expert Systems in Construction Engineering

A considerable volume of work on expert systems is in the operational prototype stage. We found four systems in the category of *Construction Engineering.*

2.2.1.1 BERT - Brickwork Expert

General Description: BERT is an interactive design aid for evaluating proposed designs for the brickwork cladding of a building. BERT examines a submitted design from an AUTOCAD system, comments on the quality of the design, and suggests improvements. The user may then edit the drawing, and cycle through the process again.

Methodology: The user inputs the design of the brickwork cladding through an IBM PC CAD program called AUTOCAD™. This input is then restructured by a procedure written in AUTOCAD's attribute file generator to a text file which symbolically describes the face of the building in question. The text file is examined by a graphical representation processor which calculates the spatial relationships between the features of the building. A current implementation of BERT will analyze the design for the proper location of movement joints. Rules about the proper location of the movement joints are located in the knowledge base of the system, which is then mapped into LUCIFER programming language rules. LUCIFER is a multi-formalism programming language whose main architecture is based on forward-chaining, although there are also provisions for backward-chaining and a blackboard type architecture, enabling the knowledge from LUCIFER to be shared by other expert systems. BERT also accesses a brick database which contains relevant details about the parameters of each of the types of bricks the manufacturer makes.

Once the design has been analyzed, BERT will recommend changes in the design, which the user may incorporate into the original design, and resubmit the design to BERT for another cycle or exit the program.

Present Status: BERT was designed in conjunction with a major brick manufacturer in order to standardize design advice to architects in the many branch offices of the manufacturer. BERT currently implements two of the five fields in which the manufacturer currently offers advice to builders. BERT was designed by J. Bowen, T. Cornick, and S. Bull from the Departments of Computer Science and Construction Management, University of Reading, UK, and is undergoing further development towards implementation.

Reference: [Bowen86]

2.2.1.2 MASON - An Expert System for Masonry Construction Duration Estimation

General Description: Estimating activity durations for a construction project is typically done by using average productivities for similar activities and adjusting according to the amount of work to be done, as well as other specific job and site characteristics. These modifications are generally based on engineering judgement and

experience. MASON is an expert system which illustrates a hierarchical, rule-based estimation approach designed to make the activity duration estimation process more systematic.

Methodology: MASON is a prototype system which provides facilities for estimating masonry construction durations, explaining the calculations involved in the conclusions,and making recommendations for crew compositions and technologies. MASON is written in the OPS5 expert system programming language. The program uses a backward chaining technique to evaluate a possible conclusion, and then tries to satisfy the supporting rules for the conclusion. One of the main system goals is to provide an estimate of an activity duration.

MASON not only has the capability to estimate duration times, but will also instruct the user on possible changes that can be made to crew size or composition, or changes in technology (e.g. using high strength mortar instead of standard mortar) that might increase productivity and shorten durations. The user may either accept or reject the recommendations. MASON does not provide facilities for giving optimistic and pessimistic duration times, nor will the program handle uncertain ("fuzzy") data.

The estimation hierarchy of MASON begins with the basic duration estimate, given crew sizes and quantities of materials. Productivity adjustments and down-time adjustments are made to the basic calculations. Once the basic duration estimate is complete, other adjustment factors are figured in, to include such things as whether the work is done inside or outside, particular labor problems, elevation of the work, and temperature. All of these adjustments are combined with the basic estimate to produce a final maximum productivity estimate for the activity.

Present Status: MASON has now undergone one round of validation. Its estimates for productivity have been found to be very close to field-observed actual productivity. The system was developed by Professors Chris Hendrickson and Daniel Rehak, and David Martinelli, of the Department of Civil Engineering, Carnegie-Mellon University.

Reference: [Hendrickson86]

2.2.1.3 RODEOS: Road Curve Design and Setting-Out

General Description: Road curve design is one of the essential tasks of the civil engineer involved with highway engineering. Once the road curve is designed, whether horizontal or vertical, the surveyor must set out the curve on the ground. The difficulty of this task varies with the degree of complexity of the design and of the surrounding construction site. In congested areas, for example, where clear lines of site are not available for setting out by deflection angles, recourse has normally been to return to linear methods, either by offsets from the tangent or long chord. Problems of access to chainage points on the center line as used in the above methods can be overcome by using the expert system RODEOS (ROad Design Expert On Setting-out). This expert systems combines design and setting-out tasks. Although this system can be described as a design system, its applicability to surveying also defines it as a construction system.

Methodology: RODEOS is a five module program written in BASIC incorporating both curve design and setting-out. It is intended primarily to be used as a field engineering tool. The five modules included are: curve design, transition curve design, circular curve design, vertical curve design, and setting-out requirements.

The program is written in BASIC to allow a greater number of users access to the knowledge through the great array of microcomputers available today. Knowledge is encoded in a rule-based production system. The program not only collects data necessary for the design of a road curve, but also selects the best method and gives a printout of the setting-out requirements.

Present Status: RODEOS has been used successfully since 1982 at the University of Stathclyde as a teaching aid to students. It has only recently become available for solving highway engineering problems with the user as client. It was developed by P.H. Milne of the University of Strathclyde's Civil Engineering Department.

Reference: [Milne86]

2.2.1.4 CRANES - Crane Resource and Evaluation System

General Description: CRANES was developed within the Department of Construction Management at Reading University to aid in the selection of crane type and crane locations for specific load/radii problems on a construction site. It is targeted for the novice user who will be able to see the range of crane options available, and for the expert user to evaluate alternative solutions to the crane selection problem. The system also evaluates the costs of the alternative solutions to the load lifting problem once the crane specifications are evaluated.

Methodology: CRANES is an integrated program which first uses a graphics program to help the user locate loads, sizes, and possible crane locations on a site plan. After possible crane locations are identified, along with the corresponding crane size and load/radii, the lifting problem is evaluated through an expert system developed in conjunction with the crane hire and manufacturing industry to determine the full specification of the tower or mobile crane.

Once the full specifications of the crane have been established, CRANES refers to an integral data base of available cranes to pattern-match the specifications from the expert system. In addition, a financial analysis of the alternative is made at this point.

Present Status: CRANES currently uses two separate computers: an AMDAHL using GHOST for the computer graphics, and a PDP/11 using PROLOG for the expert system, although there are plans to implement the system on an IBM PC or PC-compatible computer in the near future. Other possible enhancements include expanding the data base to include more crane types, parameters, and associated costs, as well as integrating the program with others to aid in predicting construction time and construction activities. CRANES was developed by Dr. Colin Gray and James Little in the *Department of Construction Management* at the University of Reading, UK.

Reference: [Gray85]

2.2.2 Operational Prototype Expert Systems in Construction Management

The largest number of expert system in any one category are operational prototype systems in *Construction Management*. We list eight such systems here.

2.2.2.1 HOWSAFE: Evaluation of the Safety of a Construction Firm

General Description: Stanford's Construction Engineering and Management Program has been conducting research into construction safety since 1969. When one considers that most construction firms do not have a complete library at the home office, much less in the field, the inadequacy of traditional methods of knowledge dissemination -- i.e., journal articles and technical reports -- for communicating this knowledge to jobsite managers becomes obvious. This need for a more convenient means of knowledge transfer to field construction managers motivated the developement of HOWSAFE.

Methodology: HOWSAFE is intended as a diagnostic tool to assist a construction manager in determining the "health" of his construction company's safety programs. HOWSAFE is implemented as a knowledge base using *The Deciding Factor*™ expert system shell, running on the IBM PC class of computers. *The Deciding Factor* employs backward chaining and two kinds of conditional logic, termed Kill Values and C-logic . The knowledge base is structured in the form of an inverted tree diagram with lower "leaf" nodes supporting higher level hypotheses ultimately proving or disproving the top level hypothesis, *"This construction firm has the required organization and procedures to promote safe construction."*

Present Status: HOWSAFE has undergone limited external validation, and is being readied for commercial use. The program is authored by Professor Raymond E. Levitt of the *Construction Engineering and Management Program* department of Civil Engineering, Stanford University. After further refinement of the program, it will be distributed along with a companion package, SAFEQUAL (See **2.1.2.2**), by *Building Knowledge Systems, Inc.*, of Stanford California.

Reference: [Levitt86a]

2.2.2.2 PROPICK: Selection of Contract Type

General Description: Nearly all construction is done by contracts, and in today's market, owners are faced with a myriad of choices concerning which type of contract to use for their different projects. Many factors affect this decision. Time and dollar constraints, flexibility to accommodate changes, quality concerns, and the current economic market are but a few of the changing inputs in the decision analysis. Moreover, clients often have internal disagreements on the relative priority of cost, schedule, facility scope and other performance objectives for a planned project. PROPICK was developed to model the decision making process used by an owner in deciding which contract type to select.

Methodology: PROPICK was developed using *The Deciding Factor* expert system shell. By analyzing user input to questions requesting from several client representatives their relative emphasis on various possible project objectives, the system performs two functions: (1) it surfaces any significant disagreements in relative project objectives among the client's marketing, manufacturing, financial and facilities engineering groups, and (2) it assists in choosing the most appropriate form of contract for the client once these internal difference are resolved.

The system attempts to determine whether traditional contract management, design/construct, or construction management is the correct basic contract vehicle for the project in question. The program also links a recommended pricing mechanism; firm-fixed price, cost plus fixed fee, or guaranteed maximum to the basic contract type. It will point out to a client who wants lowest cost, shortest schedule and freedom to make

changes that no form of contract will satisfy all of these objectives well; the client is forced to decide which objective is most important for the given project.

Present Status: The system was developed by Donald S. Barrie, president of *CM Consultants* in Diablo, California, and Consulting Professor in Stanford University's Civil Engineering department, as an aid to his consulting practice. The system is undergoing field testing and refinement at this time.

Reference: [Personal contact with Mr. Barrie]

2.2.2.3 DSCAS: Determining Entitlement under a Differing Site Conditions Clause

General Description: Most construction is performed under some type of contract. These contracts have become increasingly complex in recent years as parties attempt to limit their liability for future claims. Resolution of these claims often requires expert legal advice. However, for many reasons, parties fail to seek this expert assistance. The goal of DSCAS is to provide limited, but effective legal advice to owner representatives on a US federal government construction project.

The authors of DSCAS chose to limit their program development to investigation of differing site conditions clauses under the standard federal contract. This was done primarily because case law concerning differing site conditions under the federal form of contract is fairly well defined and self-contained. The program does not apply to local, state or private work.

Methodology: DSCAS is a rule-based system implemented in ROSIE, Rand Corporation's mainframe expert system shell, where the knowledge of federal contract management is encoded and linked through a series of IF-THEN rules. DSCAS is dependent on six major components, each of which is composed of six or more files. These six components include: driver rulesets, question rulesets, unknown answer question rulesets, conclusion rulesets, entitlement rulesets, and top level control and other peripherals.

The program steps through a check of twenty-two separate modules, each defining a finite area of the differing site condition clause. Examples of these modules include: whether final payment has been made, express or implied conditions within the contract, reliance upon the information, exculpatory language, etc. Users repond to prompted questions which will lead the program to conclude either "*Entitlement*" or "*No Entitlement*" at which point, the program ends. However, the program is capable of determining multiple justifications for entitlement.

The program was authored by Professor James E. Dieckmann and Mr. Timothy A. Kruppenbacher of the *Construction Engineering and Management Program* at the University of Colorado. It was validated through comparison with case law and it tested well. The major limitation identified during this validation was that the program at times asks question at too high a level of legal knowledge. For instance, the program asks if different soil conditions are material. Answering to this question requires legal judgement. Refinement of the program is necessary to allow it to make that judgement based on more objective responses. Additionally, the program has not been tested in a real-time environment. This is necessary before it can become a useful tool for construction managers.

Present Status: Since publication of initial findings, the US Army Corps of Engineers Construction Engineering Research Laboratory has begun revising the program

logic to correct errors and to minimize the legal knowledge required. They have also begun to rewrite the program using the software tool, *Personal Consultant Plus*™, for use on TI and IBM-PC microcomputers. Expected completion is late 1987.

Reference: [Diekmann84]

2.2.2.4 PLATFORM: Hybrid Decision Support Tool for Project Management

General Description: Traditional manual and computerized project management tools have been found to be deficient real time project control tools in part because of their inability to represent and use construction task knowledge. Because project managers are unable to devote large blocks of time to maintaining schedules for real time planning, schedule updating has become essentially an arhival record keeping process on many projects. PLATFORM was developed as an attempt to show that an Artificial Intelligence (AI) environment can represent and use construction task knowledge and hence leverage the capabilities of network-based project management systems as real time control tools.

Methodology: PLATFORM was developed in the *IntelliCorp* KEE™ programming environment. This environment is a hybrid software development environment, integrating such AI tools as frame based representation, rule based reasoning, active images, and active values, with LISP as an underlying programming language accessible for rocedural attachment to rules within knowledge bases. This integration is accomplished with object-oriented computing as the unifying methodology and allows each separate methodology to complement the weaknesses of the other. PLATFORM currently operates on XEROX 1100 series, Symbolics 3600 series and TI Explorer computers.

PLATFORM uses inheritance to store and propagate data about activities such as activity name, duration, and successors, as well as knowledge about potential risks that could impact each activity's duration in frames, termed *units* in KEE. Rules which access data stored in these frames are used to interpret past performance data and to predict future performance.

PLATFORM II, an enhanced version of the original PLATFORM, surpasses traditional project scheduling programs in its use of two-way interactive graphics for representing and modifying project schedules. In particular its live Gantt chart capability termed *GanttAlive*™ for resource leveling, provides a level of user interaction not before available in project control tools. AI techniques of active values (termed *demons* in other AI systems), and two-way interactive graphics (termed *active images*) are features of the KEE system that permitted the development of this interface, and which provide the capability for multiple rule systems (e.g., rules about cost estimating or rules about progress payments) to interface with the project data created using the graphical interface and stored in PLATFORM's activity and resource frames.

From a pure expert systems point of view, PLATFORM's most significant enhancement to traditional project scheduling packages is in automated schedule updating. During normal schedule updates, PLATFORM not only performs new forward and backward pass network computations with actual project data for completed activities, but also looks for significant risks, termed *KNIGHTS* and *VILLAINS*, which appear to have impacted the durations of completed activities. A *KNIGHT* is a risk with a favorable impact on the schedule which is shared by more than one activity; a *VILLAIN* is a risk with an unfavorable schedule impact on more than one activity. The system will seek confirmation of its identification of *KNIGHTS* and *VILLAINS*, and will then change

future activities' durations to reflect the effects of these identified *KNIGHTS* and *VILLAINS*, asking for user confirmation as it does so.

PLATFORM I was developed by Professor Raymond E. Levitt of Stanford University and Dr. John C. Kunz of *IntelliCorp*. Subsequent enhancements to the interface leading to PLATFORM II have been added by other *IntelliCorp* staff members, notably Catherine Perman.

Present Status: PLATFORM was built as a prototype to show the ability of hybrid AI-Procedural systems to enhance the power of traditional procedural tools for construction project scheduling. It currently handles networks of 30 to 50 activities at each level of detail. Subnetworking permits creation of projects with several hundred activities. PLATFORM is being extended for use in several other project management domains, including software project management and factory automation.

Existing project scheduling tools handle networks of thousands of activities for large projects in batch mode. The principles demonstrated in PLATFORM will be particularly valuable for such large, complex networks, but the limits of the interactive interface -- both computational and cognitive -- need further testing and refinement. It is anticipated that computational power issues can be addressed through links to existing scheduling packages. As a test of this, a link from PLATFORM to the *Sperry* **Mapper**™ database has been successfully built and tested. The design of suitable graphical interfaces and knowledge representation schemes to address the cognitive difficulties of dealing with large networks is continuing.

Reference: [Levitt85]

2.2.2.5 PLATFORM III - Analyzing Contingencies in Project Plans

General Description: PLATFORM III is an expert system developed to illustrate the use of the Artificial Intelligence technique of "multiple worlds" in making project feasibility decisions under uncertainty. This technique assists the project manager in making a decision involving multiple uncertainties by generating "worlds" which describe all of the possible combinations of choices available to the project manager, along with the implications of those decisions, and their outcome probabilities and values, based on user-specified evaluation criteria.

Methodology: PLATFORM III was developed using the IntelliCorp Knowledge Engineering Environment (**KEE**™), and employs the frames, rules and graphics that are tightly integrated in **KEE**.

An important feature of PLATFORM III is its ability to use the *automated truth maintenance system* (ATMS) of **KEE**, Version 3.0. The user is allowed to make assumptions regarding a decision (e.g., whether to build the land-based activities of an oil platform in Norway or Scotland), and these assumptions are used in the program to propagate the effects of the choices made. Once a line of reasoning becomes inconsistent with earlier assumptions or their implications, PLATFORM III backtracks until it can find an appropriate place to modify the search tree, without losing the previous assumptions that the user has made and their implications. These are retained in order to examine other possibilities or "worlds." In addition, the user may modify assumptions at any time, and let the program generate new worlds with new implications and outcomes.

The multiple worlds concept allows automation in the generation and evaluation of different possibilities. It also allows users to create new worlds with slightly different

facts (e.g., different cost of capital) easily and to examine their impact on the decision, or to indicate that certain worlds are uninteresting or inconsistent with specified criteria.

Present Status: PLATFORM III analyzes cost and time outcomes for each of the worlds generated, using a realistically complex time model (a PERT model with 50-100 activities) and a realistic cost function (direct costs and indirect costs, including time-related bonus/penalty amounts). The ATMS leads to rapid computation of outcome values of each of the worlds, and allows the user to browse through the facts in any world by selecting it with a mouse in a time-cost scatter diagram showing all of the worlds. PLATFORM III was developed by Dr. John C. Kunz, Thomas Bonura, and Marilyn J. Stelzner of IntelliCorp, and Professor Raymond E. Levitt of Stanford University. It is currently being used to demonstrate the ATMS capabilities of KEE, and is being extended for implementation.

Reference: [Kunz86]

2.2.2.6 Predicting Time and Cost of Construction During Initial Design

General Description: The construction industry is somewhat unique in that the processes of design and manufacturing are separated. Generally speaking, the ease of manufacture and assembly of a building may not be considered in the design process, because the designer may not have the knowledge needed for their consideration. In addition, evaluation of different methods of design requires prompt feedback regarding their time and cost implications. This expert system was developed to help designers evaluate different construction methods, designs, and processes to determine their effects on time and cost of construction.

Methodology: The expert system was developed using PROLOG. The program takes rules from construction experts, operates on a data base of common construction activities, and proceeds to model the construction site activity. An interesting feature of this system is its incorporation of nested expert systems. These nested systems are stand-alone applications as well. For instance, one of the key considerations on a construction site may be the selection of the appropriate crane for the job. The main expert system has a nested system which helps the user choose the proper crane.

Knowledge acquisition is the most difficult task for this system. It is necessary to acquire a great deal of interdisciplinary knowledge of the construction industry in order to even approach the solution to the problem. One key factor of the input to the cost calculation was discovered to be the time to construct each activity. In this respect, the researchers developing the system attempted to interlace calculation of time, relationships between activities, and resource management in order to find optimum points at which cost of activities could be minimized while staying within the parameters of time and resources. An important feature of the system is the calculation of relative construction speed between two activities. This allows planning activities to ensure that predecessors to the activities do not adversely impact on the start of the new activity. In conventional planning systems, the duration of an activity must be explicitly stated, while in this system, duration can be treated as a variable, adjusted and modified.

Present Status: This expert system, under development by Colin Gray of the Department of Construction Management, University of Reading, and J. Little of Artificial Intelligence Limited, Watford, is in the process of being ported to IBM PC class computers.

Reference: [Gray86]

2.2.2.7 Military Construction Army-Cycle Analysis

General Description: The U.S. Army Corps of Engineers maintains data on U.S. Army facilities in their various stages of planning, programming, budgeting, design and construction. While all of the appropriate data is maintained within a large data base named CAPCES, the database is not organized to extract complex, high-level questions such as, *"Why is project X so far behind schedule?"* Answering these types of questions requires some expert knowledge as well as stored data. The proposed expert system plans to use both facts stored in the CAPCES database along with stored expert knowledge about problem solving procedures to answer these types of questions.

Methodology: This expert system is being developed as a multi module system at the U.S. Army Construction Engineering Research Laboratory (CERL) under the direction of Ms. Sandra Kappes and Dr. Simon Kim. Specifically, it will incorporate natural language processing, machine learning and speech understanding along with expert systems techniques to develop a very user-friendly system. When complete, the system will be able to understand ordinary English queries, direct queries, or procedural queries; and it will have the ability to learn by example.

Present Status: Work has proceeded separately on the different modules. The natural language processor has been written in *GC-LISP*. A scheduling module has been developed in the *IntelliCorp* KEE™ environment on a *TI-Explorer* workstation. Finally, a prototype monitoring module has been developed in *InterLISP* on a *XEROX 1108*. Future work will refine and incorporate these modules into a working system. A demonstration model will be available for some of the Army's field activities in the fall of 1986 with system completion scheduled for late 1988.

Reference: [Personal contact with Ms. Kappes of CERL]

2.2.2.8 Construction Schedule Analysis

General Description: Owners of construction projects must maintain control of the contract schedule in order to make project payments and ensure timely completion of the job. They, therefore, continuously receive and review updated project schedules. Traditionally, however, less sophisticated owners tend to limit their analysis to the obvious questions: estimated start date, estimated completion date, and estimated completion cost. In doing this, these owners are presupposing that contractors have thoroughly verified their submissions. This expert system is being developed to transfer the expertise that knowledgeable project managers use in managing their projects.

Methodology: The knowledge base for this program combines construction scheduling rules, construction knowledge, and general construction experience such as effects of weather, placement rates, etc. Four major groups of scheduling decision rules are implemented in the knowledge base:

1. general requirements - such as *I-J* numbers and activity descriptions;

2. time - such as evaluation of reasonable activity durations;

3. logic - such as checking to see that submittals precede approval and construction; and

4. cost - which includes tests for total project cost and excessive front end loading.

Additionally, knowledge to revise remaining estimated duration is incorporated. The program links like activities by class; compares efficiency on completed and in-progress activities; and adjusts estimated completion on all like, remaining activities. This capability is similar in its intent to PLATFORM [Levitt85].

The program is implemented in a hybrid microcomputer artificial intelligence environment consisting principally of a project management system (PRIMAVERA™), a database management system (dBASE III™), and an expert system shell (PERSONAL CONSULTANT PLUS™). PRIMAVERA manages network data in the same way that it does in any scheduling environment. dBASE III houses not only specific project data but also non-project information such as hourly wages and productivity rates. PERSONAL CONSULTANT PLUS is an expert system shell written by Texas Instruments for use with TI and IBM personal computers. This shell uses both frames and rules to represent the encoded knowledge.

Present Status: The program is being developed by the U.S. Army Corps of Engineers *Construction Engineering Research Laboratory* under the direction of Dr. Michael J. O'Connor. A subset of the envisioned features has been successfully implemented with work continuing on completion of the entire package.

Reference: [O'Connor86]

2.3 DEVELOPMENTAL EXPERT SYSTEMS

The following systems are currently under development and have reached the stage of at least a working prototype, but have not been substantially validated and refined.

2.3.1 Developmental Expert Systems in Construction Engineering

We found two systems in the developmental stage that address *Construction Engineering* problems. They are contained in this section.

2.3.1.1 SOILCON - Soil Exploration Consultant

General Description: One of the biggest uncertainties that engineers face in construction projects is the condition of the soil below the surface of the ground. Owners generally complete only a minimal subsurface investigation, gathering enough data to produce cost estimates and a preliminary design. However, the correct evaluation of subsurface risk at an early stage of the project can have a tremendous impact on the overall success of the construction effort. It is for this reason that SOILCON was developed. This system attempts to eliminate some of the uncertainty involved in the conduct of subsurface exploration by evaluating the known conditions of the site and recommending the proper methods required to continue exploration, if necessary. SOILCON is designed to be used by the owner, in order to incorporate subsurface considerations into contract design, thereby helping to eliminate or reduce contractor contingencies and changed conditions.

Methodology: The output of SOILCON is a list of recommended site exploration techniques. If there is very little known about the site, then SOILCON may recommend preliminary testing techniques, and vice versa. Output consists of a list of recommended investigation methods ranked by certainty, displayed descriptions of those methods, and

displayed cost estimates for the methods. The system uses backward chaining from the knowledge base of rules. Basic knowledge is encoded in an IF-THEN format.

Present Status: The main drawback of the system is its inability to handle quantitative information, particularly the geometry of the site. This is due to current limitations in personal computer expert system shells, and should be remedied with newer software versions of the systems. SOILCON was developed by Professor David B. Ashley and M. Benjamin Wharry of the Department of Civil Engineering, The University of Texas at Austin.

Reference: [Ashley85]

2.3.1.2 SITEPLAN: Layout of Temporary Construction Facilities

General Description: Layout of temporary construction facilities has the potential for substantial impact on the efficiency of future construction operations. Improper site layout can lead to extensive lost time in the form of excessive travel time of workers and equipment and inefficiencies due to safety concerns. Despite this, site planning receives little advanced planning and almost no planning during construction. Too often, layout is determined by what space is available at the time the siting requirement arises. Countless material storage yards have sprung up because "there was no where else to put it" when the truck delivered the material. It is the goal of SITEPLAN to develop an expert system which not only designs a siting plan, but also can be used to update the plan continually as project time progresses.

Methodology: To solve the siting problem, SITEPLAN must solve several difficult expert system issues:

1. It must manage knowledge from multiple sources. For example, different levels of site management have different expertise concerning their operations and therefore, have different input to the system.

2. Facility siting is a two or three dimensional spatial arrangement, problem. Spatial arrangement problems are not adequately addressed by existing rule-based expert system shells.

3. Finally, temporal reasoning is a prime concern. Siting requirements change as the project progresses. Once again, rules alone have not adequately addressed this problem.

To meet these concerns, the investigators propose using the BB1 blackboard AI development architecture, and ACCORD, a specialization of BB1, both currently implemented in InterLisp. BB1 was originally developed by Dr. Barbara Hayes-Roth of Stanford University to employ and mediate between multiple knowledge sources in expert systems. ACCORD is a general framework under BB1 specialized for solving problems involving assembling arrangements of objects under constraints. The investigators will work principally on XEROX 1108 and 1186 Workstations.

Present Status: A simple working prototype of SITEPLAN has been completed. A more substantial system with expert knowledge should be completed and validated by

mid-1988. The work is being conducted by Iris Tommelein, Professor Raymond E. Levitt and Dr. Barbara Hayes-Roth of Stanford University's Civil Engineering and Computer Science Departments.

Reference: [Tommelein86]

2.3.2 Developmental Expert Systems in Construction Management

As in the case of operational prototypes, we found that the largest number of systems in the developmental phase were applications to *Construction Management*. Three such systems are described here.

2.3.2.1 IPMS85/2: Evaluation of Project Personnel Based on Progress Data from Project Time/Cost Monitoring Systems

General Description: The increased use of Management Information Systems (MIS's) in corporations has received much attention. However, instead of making the manager's job easier by manipulating the output data, MIS's have led to exponential increases in the volumes of information which the manager must digest and analyze. Although this problem has been alleviated somewhat by the use of relational DBMS's, this process sometimes lacks the flexibility it needs. What managers now need is a system which extracts the useful information from the voluminous reports generated by the computers. This need for a project data analysis system led to the development of IPMS85/2.

Methodoloy: The system developed here, called IPMS85/2 (Intelligent Project Management System), is a rule-based expert system designed to help the manager carry out evaluation of project personnel based on the data available from a typical job time/cost monitoring system data base. The system uses heuristics about project progress, personnel responsibilities, and the interactions between the two.

IPMS85/2 is built using an expert system building tool called IMST, which is written in Lisp. It is an open architecture system which uses forward chaining and includes the ability to supply explanations. In IPMS85/2, IMST was modified to allow handling relational data files from the cost accounting system.

Each object in IPMS85/2 is represented by a frame data structure, which contains slots describing the attributes of the object. For a personnel object, slots might include the job title, address, salary, and activities for which the person is responsible. A job cost account frame would include information on the account number, the estimator, the supervisor, the unit of measure, etc. Inheritance links are established through the use of *is_a* relationships.

The system uses the data from the cost accounting system reports to generate hypotheses about personnel abilities. Typically for each account there is an estimator, foreman, and supervisor. Using the costs of each activity as a starting point, the system evaluates how each of these personnel are doing in the activities for which they are responsible. For instance, if an estimator is responsible for an account, and he has an historical tendency for grossly underestimating the costs of activities, then a supervisor may not be at fault if that activity goes over budget.

The system consists of several knowledge modules which have specific functions:

1. *Classification module:* manipulates the job cost report data to calculate overruns and underruns to budgeted and actual quantities for each account. Partial information, such as plug estimates are used to complete needed data.

2. *Grouping module:* relates personnel to activities through responsibility links.

3. *Hypothesis module:* looks at the cost accounts to find problems, and attempts to hypothesize about who is responsible or performing poorly on the job. This information is placed on a "blackboard" for the confirmation module.

4. *Confirmation module:* studies the hypotheses generated by the hypothesis module and attempts to confirm them using other data from other job cost accounts and the information contained on the "blackboard."

5. *English module:* a text generator which takes the information from the confirmation module and converts the data into a more readable sentence form.

Present Status: This program is authored by Navin Chandra and Professor Robert D. Logcher of the *Intelligent Engineering Systems Laboratory* of the Department of Civil Engineering at the Massachusetts Institute of Technology. It is in an early prototype and has not yet been validated.

Reference: [Chandra86]

2.3.2.2 CPO-ES An Expert System for Construction Project Organization Design

General Description: One of the key problems in the construction industry is choosing an appropriate project organization to adequately handle the intricacies of managing large, complicated projects. Conceptual models are important as a basis for tailoring organizations to specific construction projects, but do not necessarily provide optimum results. Other intangibles also contribute to creating an effective construction project organization (CPO). These intangibles include experience, theoretical knowledge, specific skills, etc.

CPO-ES was built to systematize some of the planning processes for construction project organizations. It assists the upper-level management of the firm to analyze existing project organizations to see if they are adequate, find ways to improve them, and retain some of the knowledge and experience of project managers in the company.

Methodology: CPO-ES was built using *The Deciding Factor*, a backward-chaining program designed to help people make complex decisions by using decision trees. The top level hypothesis of CPO-ES is "The CPO suits the requirements of the project."

The questions the program asks may be answered on a scale of -5 (no, false) to +5 (yes, true). These responses are used to determine the degree of belief in the truth of subgoals and to assign reliability to the system's conclusion. The user will, after a brief 10-15 minute session, get results that indicate an overall score for the structure of the CPO, a list of questions for which more certain responses could increase the reliability of the conclusion, and a list of answers which identifies the strengths and weaknesses of the CPO being evaluated.

Present Status: CPO-ES is a prototype system and has not yet been validated. The program was authored by Dr. Rudolf Burger of *MOTOR COLUMBUS Consulting Engineers.*

Inc., Baden, Switzerland, and Mr. Martin Fischer of the *Institute for Engineering and Construction Management, ETH*, Zurich, Switzerland.

Reference: [Burger85]

2.4 CONCEPTUAL STAGE EXPERT SYSTEMS

The following systems are at the conceptual stage of development. They represent conceptual designs for systems, or systems at an early stage of development prior to the existence of a testable prototype.

2.4.1 Conceptual Stage Expert Systems in Construction Management

We found no construction engineering systems at the conceptual stage. Since many projects at this stage of development would not yet have appeared in the literature, this is not too surprising. We were, however, able to learn about five systems in the area of *Construction Management* that are in the conceptual stage at this time. This may indicate a slight shift in research emphasis over the next few years towards this area of construction.

2.4.1.1 Vertical Construction Schedules

General Description: Computerized project management systems (PMS) are widely acknowledged as deficient planning aids. Specifically, they are unable to interpret qualitative and subjective information. The construction industry, like many industries, has relied on experts to evaluate and interpret data generated by PMS. Expert systems hold promise to overcome this shortcoming. For example, expert systems should be able to reason that roofing should not normally be scheduled in winter in Champaign-Urbana, and that installation of air conditioning cannot precede procurement of air conditioning systems.

This expert system will extract, articulate and formalize: (1) empirical and judgemental knowledge about construction and (2) traditional project management theory. The overall goal is to develop an intelligent assistant capable of assisting less experienced project managers is assessing the correctness of a given project schedule, thus freeing project managers from the time consuming and tedious phases of their work.

Methodology: This proposed expert system will be implemented as a knowledge base containing both project scheduling rules such as critical path method and precedence reasoning, and common sense construction knowledge such as correct assignment of weather sensitive activities.

The expert system will be written in ART™ (Automated Reasoning Tool). This is a frame based, object oriented programming language. Because construction schedule analysis often involves analysis of different alternatives or a situation that changes in time, ART was chosen because of its "multiple viewpoints" feature which allows easy analysis of many possibilities. The system will draw information from which to base decisions from an external sceduling program.

The system is designed to operate on a TI-Explorer LISP machine housing ART along with the Relational Table Management System (RTMS™), and an IBM PC-AT housing

PRIMAVERA™, a project management scheduling program. Communication between the two computers is maintained through a serial connection.

Present Status: The system is being developed by Professor C. William Ibbs of the University of Illinois at Urbana-Champaign, Department of Civil Engineering in collaboration with Dr Michael O'Connor of the US Army *Construction Engineering Research Laboratory*. As currently scheduled, a validated prototype should be available by August 1988.

Reference: [Personal communication with C. W. Ibbs]

2.4.1.2 Knowledge-Based Project Planning and Control

General Description: Many traditional network planning programs exist for use in the conceptual stages of project development. However, these programs are generally used less for detailed operations planning or for real-time project control, principally because they have the ability only to manipulate data about project plans and not the underlying knowledge. That knowledge resides in the expert who developed the original plan. For reasons of either time or location, that expertise is frequently not available in the field. It is the goal of this proposed expert system to allow that knowledge to be transferred to the field.

Methodology: The goal of this development effort is: (1) to use knowledge about preconditions and effects of construction activities to automate the generation of detailed robot or crew-level plans, and (2) to use knowledge about construction risk factors to automate interpretation and forecasting of schedules for real-time project control. In striving for these goals, the researchers will attempt to determine the optimum "grainsize" or level of detail and degree of repetition of construction activities suitable for automated plan generation, and to further extend the PLATFORM work [Levitt85] in the area of hybrid AI-procedural project control systems.

Present Status: The proposed system will be implemented in a hybrid AI environment employing both expert systems and traditional network planning techniques. Results of this research should be available about mid-1988. The principal investigator for this work is Professor Raymond E. Levitt of Stanford University's Civil Engineering Department. The work will be carried out using *Xerox 1100* series workstations and the **KEE**™ programming environment, with InterLisp and external project management packages.

Reference: [Levitt85] [Levitt86b]

2.4.1.3 Analyzing Construction Project Risks

General Description: Management of the construction process has continually become more difficult as larger and more complex projects have been undertaken. The use of Management Information Systems has helped to guide and enhance the decision making ability of managers, and the use of relational databases and set theoretic inquiry has added even more flexibility. However, the results of the inquiries to the databases still require subjective interpretation of the results. A manager must still make inferences from the data. The work described here is a design for an expert system, rather than a working system. It proposes a system to marry the inferencing process involved in interpreting project performance with the data collection process, to determine what went wrong on a project and why. If there is a variance between actual performance and scheduled performance, the system attempts to discern the causes of the variance.

Methodology: The authors have proposed a frame-based representation of work packages to take advantage of the hierarchical structure inherent in the construction process. Tasks are defined as sub-activities of work packages, and the standard principles of inheritance are applicable to work packages involved in the same activities. In addition, frames are used to represent members of the risk component hierarchy, and factors external to the work packages. The proposed system assigns risk components to work packages, along with the associated selection and inference rules, based on the work package characteristics and the conditions of the project as a whole.

The proposed system analyzes work packages for their sensitivity to project risks and the predisposition of the work package to certain kinds of risks. Once a variance from the project plan is detected, using the data from the usual monitoring procedures available on projects, the system risk analysis algorithm is activated. Using the project data on work package performance variance, and the risk sensitivity of the work package, a risk event can be detected, and a hypothesized cause of the performance variance established. In addition, the system can establish causes of variance in other work packages with related behavior.

Once the risk events are detected, further information from the user helps to establish a hierarchy of risks along with their probabilities. In this way, the manager can help to alleviate further problems caused by the risk events.

Present Status: The system was proposed by Leston B. Nay III and Robert D. Logcher of the *Center for Construction Research and Education*, Department of Civil Engineering, Massachusetts Institute of Technology, and has not been implemented, although related work on this problem is described in section **2.3.2** of this chapter [Chandra86].

Reference: [Nay85]

2.4.1.4 Decision-Making and Risk Analysis

General Description: Project risks are a potentially serious threat to any contractor. Thriving firms are often the ones that are best able to identify and manage perceived risks. However, the ability to determine these risks is many times only resident in the most senior of company personnel. Yet much of this knowledge can be formalized. It is the goal of the this expert system to provide the mechanism for knowledge transfer so that companies can pass the ability to recognize risk to their junior, less experienced project managers. In this way, these companies can (1) protect the company from loss of corporate knowledge through retirement and transfer, and (2) free top level managers for long term strategic planning.

Methodology: This risk management expert system is developed using the expert system shell, **INSIGHT 2**^{TM}. **INSIGHT 2** was developed and is distributed by *Level 5 Research*. It is a rule-based forward and backward chaining inference engine for use with the **IBM-PC** class of microcmputers. **INSIGHT 2** also allows interface with external Pascal programs and **dBASE**^{TM} database files.

Present Status: The risk analysis program, developed by Professor Roozbeh Kangari, of the *Construction Engineering and Management* program in the Civil Engineering Department of the Georgia Institue of Technology, collects its knowledge from three sources. The initial knowledge base was collected from published journal papers and textbooks. After that, interviews were conducted with a collection of contractors having over ten years construction experience managing companies of less than $50 million

volume. Types of knowledge include the amount of liquidated damages versus project duration, amount of existing workload, and quality of client/contractor relationship. The system is still under development.

Reference: [Kangari86]

2.4.1.5 ICT - Time Estimating System

General Description: Construction firms are frequently asked to provide time and cost estimates for projects whose scope is only very loosely defined. The expertise to do this in a manner that results in a competitive, yet profitable, time and cost estimate is very scarce. Consequently, the Indicative Construction Time (ICT) expert system is being developed by *Civil and Civic*, a major construction firm in Australia, to permit the firm to respond quickly and competitively to such inquiries from clients with a realistic schedule. The cost estimate is not addressed by the current phase of ICT.

Methodology: The system is being developed by *Civil and Civic* in collaboration with *Digital Equipment Corporation's* AI applications group. The system is being built using a proprietary new AI development language that DEC is designing and which will run on DEC mainframes. No other details of the system architecture or hardware were available at press time.

Present Status: The system is planned to be completed about June of 1987.

References: [Personal communication with Alan Stretton of *Lend Lease*, the parent corporation of *Civil and Civic*]

2.4.2 Conceptual Stage Expert Systems in Maintenance

Only one system was found in this category. The area appears to be a natural for commercial exploitation, however, and it is possible that many more such systems of a proprietary nature are under development but have not yet been publicized.

2.4.2.1 Maintenance Advisor for Old Elevators

General Description: Maintaining older elevators was becoming more and more of a problem for *Elevators, Pty. Ltd.*, an elevator construction and maintenance firm in Australia. The knowledge required to diagnose and repair older elevators was rapidly being lost from the industry as older mechanics retired or died. Consequently, one of the best repairmen in the company has embarked on the development of an expert system that will encode much of his knowledge about diagnosis and repair of older model elevators for use by less experienced mechanics.

Methodology: The company is using *Expert-Ease*™, an inductive rule generation expert system shell based on Quinlan's research on machine learning [Quinlan79], and running on **IBM PC** computers. In this system, the user provides the knowledge in the form of a series of examples or cases with attributes and their values, where the final attribute and its value represent the dependent variable or advice -- in this case a diagnosis and suggested repair strategy for the malfunctioning elevator. *Expert-Ease* induces a set of rules which will most nearly produce the correct advice, given the minimum necessary attribute values.

Present Status: Work on this system is proceeding towards a set of testable knowledge bases sometime in 1987.

References: [Personal communication with Alan Stretton of *Lend Lease*, the parent corporation of *Elevators, Pty. Ltd.*]

3. Conclusions

Considering the widespread view of construction as a conservative industry, it may be surprising to some readers that so much work has been done in attempting to apply this new computer technology to construction problems. In the introduction, we provided several arguments for why this technology may be especially valuable to decision makers in construction. The extent and breadth of work already completed, under way, or in the early conceptual stages described in the previous section indicates that many researchers and practitioners in the construction industry see expert systems as offering new and potentially valuable capabilities to support decision-making in the industry.

In conclusion, we will provide some analysis of the applications described in this survey, and some thoughts about possible directions for ongoing and future development work in this field.

3.1 EXTENT OF WORK TO DATE

The US construction industry has been widely criticized for its failure to commit funds and effort to research and development. By the most generous estimates of the *Construction Industry Institute*, total federal and private expenditures for basic construction research amount to no more than about $10 million per year in a $300 billion per year industry.

Against this backdrop, it is particularly interesting to tally up the amount of effort that has gone into research and development of expert systems in construction over the past few years. If we assume that each operational expert system reported here involved five person-years of effort, each operational prototype has involved three person-years to date, and each developmental expert system has involved one person-year to date, we reach a total of:

Operational Systems:	**6 x 5**	**= 30 person-years**
Operational Prototype Systems:	**12 x 3**	**= 36 person-years**
Developmental Systems:	**5 x 1**	**= 5 person years**
TOTAL CONSTRUCTION:		**71 person years**

If we price a person-year of research or development at $100,000 (to include overhead costs), we can estimate a cumulative investment of about $7 million in building expert system prototypes by the researchers and practitioners whose efforts we have reported here. Thus the volume of work performed by the pioneers in construction expert systems

in the US and abroad over the last two or three years is comparable to the total annual basic research conducted in the US construction industry! Clearly this is an active area of research and experimentation.

3.2 DISTRIBUTION OF CURRENT APPLICATIONS

We can classify expert system applications in construction in two ways: by stage of development, and by application area. **Table 1** shows this breakdown.

	Operational	Operational Prototype	Development	Conceptual	TOTALS
Construction Engineering	1	4	2	-	7
Construction Management	2	8	3	5	18
Repair, Rehabilitation, & Maintenance	2	-	-	1	3
TOTALS:	5	12	5	6	28

TABLE 1. Distribution of Expert System Applications

From Table 1, we can see that the volume of expert system work carried out in *Construction Management* has been more than twice as high as in *Construction Engineering*. In addition, it is striking to note that, aside from one relatively modest maintenance application, all of the reported conceptual stage work is being done in *Construction Management*.

This result may be merely an artifact of the voluntary nature of the information provided in our survey. It is quite possible that a great deal of expert system work is being conducted in the area of *Construction Engineering* by equipment manufacturers or others who are not yet ready to disclose it. However, we doubt that this is the case. Perhaps expert systems will prove to be more valuable for managerial kinds of decisions than for technical decisions in this industry.

Note also that projects reported show a good balance between developmental and operational systems. One would expect operational systems to be better represented in our sample, since many conceptual or developmental stage systems have not yet resulted in

publications. There are probably many more projects in the conceptual stage that we have not reported. We interpret this to indicate a long term commitment to expert systems research and development in construction by academics and practitioners in several countries. One can confidently predict active research efforts in this area for the forseeable future.

3.3 POSSIBLE FUTURE TRENDS

It is always hazardous to forecast technology futures, but with the appropriate disclaimers, we will attempt to do so. Two factors that we can assess reasonably well are likely to influence the direction of future applications in construction: the evolution of hardware and software for developing and delivering expert system applications, and the themes currently being addressed by systems in the conceptual stages of development. We will summarize each of these and draw some implications from them.

3.3.1 Hardware and Software Technology for Expert Systems

Although it is difficult to predict the exact configuration or cost of future hardware and software for expert systems, the general trends are quite clear:

- Costs of personal computers are beginning to bottom out as keyboards and monitors become their most costly components, but the performance of such systems continues to grow. Powerful battery-operated laptop machines with several megabytes of RAM, and capable of enduring the rigors of construction sites, are already available.

- Such computers already permit the use of expert system programming environments that exceed the capabilities (and far exceed the ease-of-use) of MYCIN and PROSPECTOR, the mainframe-based expert system languages that launched this technology. We expect to see estimators, project engineers, and others walking around jobsites with such computers, running expert system applications that communicate by radio with programs or data in a site or home office, within the next few years.

- The next generation of personal workstations will support the high-end AI environments such as *IntelliCorp's KEE*™ system or *Inference Corporation's ART*™ system. It is difficult to predict whether construction engineers will find uses for these advanced expert system environments on portable computers, but the author is confident that problems such as project scheduling or design and layout of temporary facilities will be conducted at construction jobsites using the next generation workstations and such programming environments within a few years.

- The LISP workstations which currently support languages such as KEE and ART are rapidly falling in price. Texas Instruments claims to have designed such a machine on a single chip, so that future size and price drops are likely. These machines are currently being used only in developmental work in construction. As their price, size and ease-of-use improve, they may become hosts for operational systems.

- The software tools available for building expert system applications in construction have improved dramatically over the last five years. Systems that can run on IBM PC™ computers and which were used by developers of the applications described in this chapter already offer outstanding ease of use (*The Deciding Factor*), the capability to interface with external data and programs (*Insight2+*) and even support

of frames (*Personal Consultant Plus*). We can expect continued gains in performance/prices ratios, and also enhanced capabilities over the next few years.

- Moreover, the developers of the most sophisticated expert system programming environments (notably *IntelliCorp* and *Inference Corporation*) and certain manufacturers of the LISP workstations needed to host them (*Texas Instruments* and *Xerox*) have made their products available to construction researchers at affordable prices in order to seed research on more sophisticated expert system applications. We now see the first such hardware/software environments being purchased by construction firms. This will permit interaction and cross-fertilization of ideas through the exchange of knowledge bases built using the most powerful tools currently available. It provides cause for optimism.

3.3.2 Themes in Conceptual Stage Development Work

We believe that much of the future research and development of expert systems in construction will involve hybrid systems combining expert systems with database management systems and computational systems.

- With one exception, the projects that we classified as conceptual stage expert systems are concerned with decision support for management of construction projects. Considering the widespread use of sophisticated project scheduling packages, and the enormous resources that are currently devoted to generating project plans and updates, this area would seem to offer substantial commercial potential. Project management software vendors, contractors and others are, therefore, viewing this application area with considerable interest, and we suspect that proprietary efforts are already underway to explore the potential uses of expert systems in leveraging the capabilities of traditional project management tools. We predict that this will be a major area of future research and development for expert systems in construction.

- A second, related area for fundamental research and development on expert systems in construction is likely to be the use of expert systems for integrating between design and construction decision-making. **CADBASE**, the structural design and construction cost estimating hybrid expert system developed by Craig Howard and his colleagues at Carnegie-Mellon University [Howard86] is one of the forerunners of such systems (CADBASE was not described in this chapter since its focus was more on structural design). In such hybrid systems, expert system programming approaches will be used to develop individual expert system modules, as well as to communicate between these multiple "knowledge sources" and other expert systems, databases and application programs.

- A relatively unexplored application of expert systems in construction is the potential to interface expert systems to CAD systems which can attach non-graphical attributes to their graphical objects. The **BERT** system described in **Section 2.2.1** points the way towards this type of application. Systems of this type offer the promise to move us towards *Real Time Engineering*, in which the graphical representation of a project, with its attached non-graphical attributes, forms a pictorial database that can support design, construction and facility management decision-making needs from a central database in real time. We predict that expert systems will play a strong role in this type of hybrid computer environment, too.

- Finally the area of diagnostics for inspection, maintenance and repair is likely to be an area where many small systems, residing on desktop or portable **IBM PC**™ or

similar personal computers, will be developed. The level of effort required to produce useful systems, and the low cost, standard hardware and software make it easy to justify their development, even with present technology. Future advances in ease of use and power will make such projects even more attractive.

4. Acknowledgements

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Chapter Three
Expert Systems in Structural Engineering

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Expert Systems in Structural Engineering

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1 INTRODUCTION

This chapter presents the current state of expert systems as they apply to structural engineering. While all efforts have been made to be comprehensive, I am fully aware that I missed a lot of the good work in progress. No slight is intended toward anyone in the field and I would certainly appreciate hearing from anyone working in the area. As noted in the conclusions, one of the current problems for expert system work is a lack of a central clearing house for work in progress. Thus, as the chapter will show, some areas are being heavily concentrated upon while others are virtually untouched. It is hoped that this report will help to bring a more uniform effort level to the application of expert systems. I once again urge those not mentioned to inform me of their efforts and please accept my apology for not including you.

All efforts have been made to be accurate in reporting the information contained herein. Unfortunately, mistakes are made. I would greatly appreciate notice of any mistakes, errors, or omissions made; and acknowledgments that were not made. In this fashion, future editions may be more accurate. Apologies are extended for any errors made.

1.1 What Is Structural Engineering

Defining what constitutes "structural engineering" is a little like trying to get a firm grip on a Jello elephant. Many universities teach structural engineering and can promptly list which courses are part of their program. Practitioners will paint a quite different story. As a result, I have chosen to define structural engineering as encompassing any and all areas that a person calling him/herself a structural engineer would do. Thus, the classical areas are included, but also covered are some areas (e.g., building maintenance) that might otherwise slip through the cracks. While some purist might be offended, it must be remembered that this chapter is intended to cover all expert systems topics of interest to structural engineers. I felt it was far better to be inclusive than to skip an item of importance to a few. This approach has also led to some overlap with other chapters of the report and people on the fringe of "structural

engineering" must read the entire report (a good idea anyway).

I have chosen to divide the topics up as follows. This is similar to Merritt's book, "Standard Handbook of Civil Engineering". I believe it forms a sufficient umbrella to classify the existing expert systems work. This break down will be used throughout the chapter.

1. Materials
    1. Cementitious
    2. Metallic
    3. Organic (Timber and Plastics)
    4. Soils
    5. Composites

2. Structural Analysis
    1. Loadings
    2. Static Analysis
    3. Dynamics and Vibrations
    4. Finite Element Approaches

3. Code Checking
    1. Concrete Codes
    2. Steel Codes
    3. Timber Codes
    4. Building Codes (e.g., BOCA)
    5. Related Codes (e.g., electrical plumbing, NRC)

4. Structural Systems
    1. Buildings
    2. Bridges
    3. Tunnels
    4. Retaining Walls and Foundations
    5. Tanks, Vessels, and Boilers
    6. Piping and Conveyance Systems

5. Miscellaneous
    1. Utility Systems
    2. Maintenance Issues
    3. Inspection
    4. Computer-Aided Drafting

A few notes are in order. First, computer-aided drafting should not be confused with computer-aided design. Design problems I have put under one of the other categories, usually structural systems. Computer-aided drafting only refers to graphical approaches and generic drafting systems. Second, only the primary level of decomposition is used for organization; the secondary level is more for example than organization. Perhaps as the number of expert systems grow in the next few years, the

secondary level of classification will be needed. Third, finite elements are placed separate from other analyses for organization only; they are, of course, types of static and dynamic analyses. Fourth, some of the expert systems described are more general and cover more than one topic. I have sorted them by what I felt was the most prevalent item covered. This is particularly true of material related expert systems.

1.2 Overview Of Structural Expert Systems

This section provides a general overview of where all the expert system work has been done. Individual experts systems are not discussed here, but are detailed in the sections on "Operational Expert Systems" and "Developmental Expert Systems". A large number of references are given, making it somewhat difficult to read; I suggest delaying a review of the references until having read the complete section.

1.2.1 Introductory Papers

Artificial intelligence has been a topic of discussion among engineers and designers, particularly in academia, for over two decades. Only recently has it matured and the subtopic of expert systems appeared as a viable approach to design. It is important to realize that while this report deals only with "expert systems", other aspects of artificial intelligence are being considered [Rooney82a, Rooney82b].

Many authors have described what constitutes an expert system in a variety of forums such as keynote addresses [Fenves86]. Some have focused upon the characteristics [Kostem86b], others have tried to tie them into a general topic [Dym85b], and yet others to use a historical approach [Rasdorf84]. Some authors have presented the material as introductions to books and conferences [Gero83a, Gero85a, Gero85b, Gero85d, Gero86c]. Some reports are even concentrating on the efforts of one particular location [Rasdorf85a].

Some of the introductory papers are survey papers concentrating on all expert system work within a particular topic. Two papers have examined the building industry in the United Kingdom [Wager84b, Marksjo85a], and one has focused upon experience in a United States engineering construction firm [Finn86]. Six papers have summarized structural engineering in general [Furuta85, Singh85, Adeli84, Adeli85, Sriram84, and Wager84a]. Proceedings from sisters societies to ASCE, such as the ASME [Dym85a], also contain summary survey papers that are relevant. Architectural expert system surveys can provide information too [Coyne85c, Gero84a, and Gero85c].

Expert Systems in Structural Engineering

A number of papers written by civil engineers for civil engineers have been publisned about the techniques used in building expert systems. A particularly active topic is knowledge and knowledge bases for expert systems building [Rasdorf85b, Rasdorf85c, Rasdorf86a, Gero86a, Gero86e, Coyne85a, Coyne85b, Coyne86a]. Knowledge acquisition has received limited attention examining the value of expert system opinions [Wong85a], rules of thumb [Radford84a], and handling expertise from multiple experts [Dym85c]. Tools have become more of an issue as the number of tools have increased. Conference papers [Maher86, Ludvigsen86] have been presented summarizing tools and techniques in general. Specific languages such as Prolog [Gero86b] are being examined along with some custom shells [Rooney86]. Yet other papers are beginning to address specific programming approaches for the development of shells [Coelho]. Most papers begin with a general overview which can be helpful for the novice to expert systems. More recent papers, however, are shying away from repeating the routine introductions as many in the field are quite familiar with expert system history and space for paper publication is becoming increasingly tight.

1.2.2 Materials

An area that is particularly sparse is the application of expert systems to structural materials. This seems particularly odd due the importance and number of difficulties that structural engineers face with materials. I have included individual component design here, but still little exists. Some of the material on "Codes" could be applied to materials, but "Codes" is also a sparse area. Only one paper could be found on general techniques to component design [Evans86], and only one paper on composite material design and analysis was found [Zumsteg85].

1.2.3 Analysis

Loading advisors and programs analyzing the effect of certain types of loadings comprise the bulk of the analysis related expert systems. A general loading advisor has been developed [Rasdorf85d], but little is known about its capabilities. Systems for aiding in offshore loading analysis [Jain84], reinforced concrete under severe loadings (such as blasts) [Krauthammer86], and for seismic related evaluation [Miyasato86a, Miyasato86b] have been documented. A system has been developed to employ learning in a simple beam design [Rooney82b]. Some systems for use in educational environments have also been written [Connor85, and Slater86]. Some papers have begun to examine the impact of expert system techniques on analysis: Interlisp programming environments [Adeli86b] and fuzzy sets [Wong86b].

Expert Systems in Structural Engineering

Finite element analysis has employed expert system techniques and artificial intelligence for many years due to the complexity of analysis. Only lately have these techniques been identified as belonging to the more general class of expert system techniques, and thus, many of the techniques go unnoticed. SACON [Bennett78] is one of the more famous experts systems in structural engineering. It provided guidance in using the MARC finite element analysis program for novice users. A similar program SESCON was built for the SESAM-69 program [Fjelheim83, Rehak85]. Recently some authors of finite element papers are displaying their wares in the expert systems arena [Grerory86].

Expert system technology has not been applied to formal optimization to any extent yet, though the potential certainly exists. Only one paper in building and urban design has examined optimization and expert systems [Sharpe86b].

1.2.4 Design Codes

Many programs have been written for checking design codes and special techniques such as decision tables have been explored. Experts systems and artificial intelligence natural language processing would seem a natural spot for handling design codes. Code complexity has largely slowed the introduction of the new techniques, but some work is under way. Consideration of design codes as a source of expertise has been examined [Rosenman85] and a prototype system built [Rosenman86]. Another approach has been a more generic look at building approval [Marksjo85b].

1.2.5 Structural Systems

By far, the structural system design area has been the most active. Papers dealing in generalities exist [Sharpe86a, and Adeli86a]; the former deals with CAD expert systems and the later looks specifically at LISP.

Design synthesis has been looked at quite heavily by the Australians. A logical model has been proposed [Coyne86b], and developments in design synthesis have been reported [Gero86d]. Object modeling and pattern recognition for synthesis have also been explored [Gero84b].

Space and structural system layout have had numerous systems built. Mathematical modeling has been used [Sharpe85] along with some Australian efforts in modeling [Akiner84, Akiner86]. Representations for describing what's what and what's where have also been examined [Gero83d]. A major effort in system layout has occurred at Carnegie-Mellon University with Ph.D and M.S. theses in a coordinated effort. HI-RISE [Maher84, Maher85a, and Maher85b], an expert system for configuring the structural system

for high rise buildings, has received the most attention. But several related projects have also been completed or are under way: LOW-RISE [Camacho85] configures low rise industrial type buildings, DICE [Barnes84] is the graphical system for HI-RISE (not exactly an expert system, but in the family of systems), FLODER [Karakatsanis85] another floor layout system using OPS-5, ALL-RISE [Maher86b] an improved version of HI-RISE, HI-COST a cost estimating system for HI-RISE [Howard83], and Destiny [Sriram84] an extended version of HI-RISE adding more configurations and capabilities.

Structural and architectural detailing is the other extreme to systems like HI-RISE. Two papers have addressed the architectural detailing issue [Radford85a, and Radford85b]. A cost evaluation system for house building (house building is often considered in the realm of detailing by structural engineers) has also been prototyped [Woodhead84].

The remaining expert systems for structural system design concentrate on specific problems. Generally, the system developers were looking for an in-depth expert system as opposed to the breadth-first approach taken by many. A system for designing bridges has been developed at Duke University [Welch86]. Wind bracing problems have been attacked using adaptive expert system techniques [Arciszewski86a, Arciszewski86b]. A system called DEST-I has been developed for the design of oil storage tank supports [Fukuda85a, Fukuda85c]. A system for the design of earth retaining walls has been programmed [Hutchinson85]. A system called PRIDE has been created for designing paper handling systems [Dym85e].

1.2.6 Miscellaneous

As was stated earlier, "structural engineers" are called upon to perform a number of tasks which are not design in nature. These are still relevant to "structural engineering" as defined earlier, and thus, will be included here.

Maintenance of structures is a problem that many structural engineers devote their professional careers to. A system has been developed to diagnose the cause and cure of moisture related problems, called DAMP [Sachdeva85]. A system for diagnosing the cause and cure of mechanical and structural failures in pumps is commercially available [Rooney85, Finn86]. A welding defect advisor has been created (as part of a welding family including a welding procedure selector and a welder selection system) [Finn86]. In the same commercial family is a system for diagnosing the causes of vibrations induced in large commercial fans.

Expert Systems in Structural Engineering

Inspection and damage assessment is performed by many structural engineers. Quite a number of research efforts have been concentrated in these areas. A system to aid in the rating of highway bridges has been prototyped [Kostem86a]. SPERIL-I and SPERIL-II aid in the evaluation of seismically damaged structures [Fu84, Ishizuka82]. Similar systems have been built for seismic damage [Yao84]. Another effort, called DAPS, has been made to assess damage to protective structures (e.g., military enclosures) [Ross86a, Ross86b, Ross86c, Bhagat86, and Wong85]. A specific paper on the use of PROLOG for preventing structural failures also exists [Fukada85b].

Developers of graphical approaches and computer-aided drafting systems have sought expert systems to improve both performance and sales. The use of knowledge based systems has been examined [Vora86, Dym85d, Gero83b, and Gero83c]. Specific work has been done for tools like PROLOG [LeTexier85], and for specialty structures like 3-D steel frames [Pesquera84].

As noted earlier, a number of systems not in structural engineering may apply based upon which fringe of structural engineering is at hand. Site planning has been assessed [Findikaki86, and Law86]. Hydraulic related systems for flood estimation have been written [Fayegh86]. Environmental related systems for hazardous waste incineration and processing exist [Law86, and Huang86]. A separate section of this report deals with construction and includes systems for construction scheduling [Levitt85, and O'Conner86], and construction risk/safety analysis [Kangari86, and Levitt86]. Even some pattern recognition for remote sensing could apply to structural engineers and has been examined [Maser86]. Obviously, structural engineers in other fields should examine their roles and determine all parts of this report that could apply.

1.3 Reasons For Using Experts Systems

The reasons for using experts systems in structural engineering are the same as for using any type of automation: using less skilled personnel, quicker solutions, and more reliable solutions. Some may wish to add that by removing tedious operations, employee satisfaction will increase. The bottom line is reduced costs!!!

Expert systems differ from conventional techniques in several ways which have been outlined many times before. For the structural engineer, their biggest advantage is the ability to process non-numerical data and express procedures in more understandable "English" like rules.

2 OPERATIONAL EXPERT SYSTEMS

This section provides descriptions of structural engineering experts systems that are of an operational nature. A system is considered operational if it contains sufficient expertise to be used in practice and has an adequate user interface for practitioners.

2.1 Commercial Experts Systems

Commercial expert systems are a subset of operational expert systems. Systems in this subcategory meet the requirement of having been verified for commercial usage. This verification may have been: an elaborate alpha-beta testing procedure (e.g., Pump-Pro), input of expertise from commercial practicing experts, review by commercial practicing experts, or acceptance of the product through actual usage by commercial companies. While only actual usage proves that an expert system is of commercial value, verification is essential to establish that an expert system will give sound and correct advice to the practitioner. This step is crucial, but often overlooked in much of the expert system development being done.

2.1.1 Material Related Commercial Expert Systems

2.1.1.1 Welding Advisor

General Description - The multitude of materials, harsh environments, variety of welding equipment, and complex regulatory codes make the selection of a proper weld procedure a difficult task. Further, this procedure must be selected before estimates can be made of the welding supplies needed, and subsequently the costs involved. The weld procedure selection program assists in choosing the correct welding procedure based upon the types of materials involved and the weld configuration. Additional information is asked as required to narrow selection to a single procedure. Then, specifics about the length, depth and other geometric features of the weld are requested, if not previously given; and an automated estimate of welding supplies is generated along with any special equipment that may be needed. The system is currently "limited" to ASME codes (this restriction is not really very limiting as ASME covers most cases).

Methodology - The program is a general configuration selection type implementation with an added computation segment for performing the estimates. It operates in a spreadsheet type environment and was constructed in LOTUS 1-2-3 making extensive usage of the macro capabilities. The result consists of approximately 150 rules coded as macros driving the weld configuration portion of the program plus the standard spreadsheet computation formulae for deriving the estimates. The process took about six man-months to complete.

Expertise for the project was provided by Stone & Webster Engineering welding expert Bill Hathaway who also provided the majority of the programming. Guidance was provided by the Stone & Webster Engineering artificial intelligence team of Gavin Finn and Martin Rooney. Verification was completed by the expert Bill Hathaway and subsequent field usage within Stone & Webster.

The system operates on company wide IBM-PC installations and can also be accessed by telephone dial-in to an IBM-PC configured to run the complete line of Stone & Webster's expert systems. Though speed is adversely affected by telephone transmission, the expert system in a stand alone mode is extremely fast. Loading of the knowledge base does take a minute or more from floppy disk configurations. Additional welding codes are being considered for implementation.

Reference - [Finn86]

2.1.1.2 Weld Defect Advisor

General Description - Welds abound in structures like power plants, process control plants, and buildings with metallic structural systems. Regardless of the care taken, the variety of welding procedures, welding supplies,welding materials, and welding environments result in numerous weld defects. It is necessary to diagnose both individual weld defect problems and systemic welding difficulties. Cost control and structural integrity along with conformance to code requirements are the primary driving factors. The weld defect advisor addresses this need.

Methodology - The weld defect advisor aids in 1) diagnosing individual causes, 2) diagnosis systemic causes, and 3) providing advice to prevent recurrence of the poor welds. The system is a backward chaining diagnosis approach. It is implemented on a commercial expert system shell called EXSYS and was designed to run on an IBM-PC. Additional features are being considered through the use of an animated graphics program called STORY-BOARD. The system consists of approximately 150 rules and

required six man-months to complete.

The source of expertise, verification process, and use are the same as the Welding Advisor described in section 2.1.1.1.

Reference - [Finn86]

2.1.2 Analysis Related Commercial Expert Systems

2.1.2.1 Seismic Risk Analysis System

General Description - The seismic risk analysis system is designed to provide consultation on the potential safety of a structure. It considers factors such as ground motion, structural vulnerability, and social impact (or building importance) of potential damage.

Methodology - The seismic risk analysis system was developed at Stanford University using a commercial expert system shell called DECIDING FACTOR. It is a backward chaining diagnostic type approach. It works backward from overall rating asking questions to determine appropriate rating changes and to determine additional questions that need to be asked. The shell provides a very flexible response allowing for certainty about each answer to effect the final rating. Explanation features are also available through the shell.

The system is designed to run on an IBM-PC machine with 128K bytes. Currently it can only be run by possessing a copy of the rules along with the shell.

Validation was performed on the system by comparing the expert system's consultation and rating with that of an expert across a sample of five buildings. Comparable results were obtained using the human expert and the expert system. A more extensive evaluation is underway. It should be noted that the model is still considered somewhat limited by the developers, but it will function properly within its domain limits.

Reference - [Miyasato86a, Miyasato86b]

2.1.2.2 Damage Assessment Of Protective Structures

General Description - DAPS, an acronym for Damage Assessment of Protective Structures, is a system constructed by the U.S. Air Force to project possible damage to protective structures, such as underground bunkers, to intense impulsive loads, such as blasts. The process is judgmental based upon a combination of damage descriptors and damage levels; which led to notions such as functionality and repairability.

Methodology - DAPS is a backward chaining diagnostic type program attempting to infer a rating and select appropriate questions as it progresses. It is implemented on a commercial expert system shell called EXSYS and intended to run on an IBM-PC class machine. Originally a shell called SPERIL-I, actually coded in C, was considered. Uncertainty, as provided by the EXSYS shell is a key to operation. Explanation facilities are available.

The program is based upon and verified against a series of eleven experimental tests on buried reinforced concrete boxes subjected to explosive pressures. Data on instrumentation waveforms and survey sheets from human experts on damage were collected and form the basis of the system.

The DAPS project is a joint venture between the U.S. Air Force, Weidlinger Associates, and Washington State University. Ownership is that of the U.S. Air Force.

Reference - [Ross86a, Ross86b, Ross86c]

2.1.3 Code Checking Related Commercial Expert Systems

No systems in this category were found.

2.1.4 Structural Systems Related Commercial Expert Systems

2.1.4.1 Retaining Wall Design System

General Description - RETWALL is a retaining wall design program. It is different from other retaining wall design programs (i.e., those of a conventional form) in that it can select between classes of retaining wall types and between different prototypical cross sections. Inquiry is made about the soil and topological conditions as well as designer's preferences.

Methodology - The RETWALL system was developed at the University of Sydney in Australia and implemented in the BUILD expert system shell. It is a configuration type program with some backward chaining to identify key parameters. Extensive use of graphical interfaces set this program apart from many other expert systems. BUILD was implemented on a SUN Microsystems SUN-2 Workstation in Quintas Prolog.

Much of the information in the system, which has written by P. Hutchinson, was not available in formal form (e.g., textbooks). Specialist engineers were surveyed for the information, plus experience by the developer was added. This approach provided much of the verification of the system.

Reference - [Gero86d, Hutchinson85]

2.1.5 Miscellaneous - Maintenance Related Commercial Expert Systems

2.1.5.1 Moisture Damage Diagnosis

General Description - DAMP, an acronym for Diagnostic system for Architectural Moisture Problems, is designed to consult on the cause and possible solutions for damaged caused by moisture. This task is conventionally performed by building inspectors and can require long waits for a simple consultation. This system should provide quick solutions for most moisture related difficulties.

Methodology - DAMP is a backward chaining diagnostic system with a very simple question asking user interface. A simple rule based approach is used implemented in Interlisp running on an IBM 4341. Approximately 150 rules drive the system identifying the cause of the moisture damage and suggesting remedies as appropriate.

The system is based upon knowledge acquisition from a human expert at the Building Research Association of New Zealand, Harry Trethowen, over a number of sessions. After completion, the system was presented to the expert for final verification, and agreed with the expert in most cases. Further, the expert has used the system to help diagnose some real life cases. As cases occurred which the system could not diagnose, the knowledge base has been updated to encompass the new solutions. The explanation facility was considered by the human expert to be invaluable.

Reference - [Sachdeva85]

2.1.5.2 Pump Diagnosis

General Description - On occasions, piping structural engineers and building maintenance structural engineers are called upon to diagnose a problem with a pump. Pump-Pro is a diagnostic program designed to aid pump-mechanics, millwrights, and those not familiar with pump operation. The system uses a four step approach: 1) identify major symptom(s), 2) identify causes or eliminate non-cause, 3) suggest remedial action where advisable, and 4) provide tutorial information as required during the diagnostic session. The system will handle single or multiple cause problems.

Methodology - Pump-Pro is a forward chaining diagnostic system developed at Stone & Webster Engineering Corporation. The system is developed using an internally written forward chaining natural language shell called MAIDService (Microcomputer Artificial Intelligence Diagnostic Service) developed by Martin Rooney [Rooney86]. This shell runs on an IBM-PC based machine using production rules. The rules are written in a subset of English and compiled into a secure knowledge base that is then run by an Executor which performs the actual interaction with the end-user.

The system handles twenty-two possible symptoms providing tutorials with each question plus seven extensive tutorials on fundamental underlying concepts if the user is uncertain and the information is necessary for diagnosis. The final system contains over 460 rules.

The system was designed to be disk based to remove the memory restrictions of microcomputers. As a result, system performance is closely tied to the disk configuration of the particular microcomputer, yet can run on a machine as small as 128K of main memory and two 360KB floppy disks. On an IBM PC-AT with a hard disk, processing runs at approximately 20 rules per second. Exact time for diagnosis of a problem depends upon the number of rules necessary to determine the cause.

Several special user interface features enhance the program. Help keys have been provided. A key to allow the user to back up and change the answer to a question, and a key to stop and save the current solution at any point are available. An option to print a hardcopy of a given session is included which details the logic used to arrive at the final solution.

Expertise for the program was provided by T.J.Fritsch and expert system work was performed by M.Rooney and G.Finn, all of Stone & Webster. After completing the knowledge base, extensive

testing of the system was performed taking over 6 months to complete. Testing included running numerous example cases provided by the expert and other pump experts employed by Stone & Webster; these included single and multiple cause problems as well as cases where no problem existed. After this internal testing was complete, the system was beta-tested at a field site in Louisiana by construction personnel. Finally, the system was reviewed by Corporate management and then released for distribution. Currently more than 400 copies of the program have been sent to Stone & Webster clients, and custom versions of the program for a major chemical company have been produced.

While designed to run on any IBM-PC class machine in stand-alone mode, Stone & Webster also provides a dial-in service to its expert system family. Pump-Pro is available on that dial-in service. Considerable speed reductions are encountered in this mode due to the large amount of data that must be transmitted.

Reference - [Rooney85, Rooney86, Finn86]

2.1.5.3 Vibration Diagnosis

General Description - Diagnosis of vibration problems with large industrial rotating equipment often falls within the domain of a structural engineer. Stone & Webster's vibration monitoring program is an aid to engineering personnel to diagnosis problems with both new and in-service rotating equipment. While written primarily to diagnose vibration problems in large industrial fans, the system is also useful for all types of rotating equipment. The input to the program begins with spectral response data; thus, the program is definitely not intended for a beginner. Other data is asked for depending upon the spectral response data, such as specifics about the configuration of the fan.

Methodology - The vibration monitoring program is primarily a backward chaining diagnostic approach. It has been implemented on two systems, and thus, has been used by Stone & Webster for comparison of expert system shells. One version was programmed using a version of Mini-MYCIN and runs on a VAX 11/780 machine. The other version, the more commonly used, was written using a commercial expert system shell called EXSYS and runs on an IBM-PC class machine. Because EXSYS will soon issue a version for VAX machines, plans exist to move the EXSYS version to the VAX also. The system contains approximately 200 rules and took one man-year to complete. The program may be run stand-alone on an IBM-PC or may be accessed through Stone & Webster's dial-in expert system service.

Expertise for the program was provided by the Vibration Analysis Group of Stone & Webster Engineering, primarily Jack Hall, and expert systems works was done by Gavin Finn. After the system was completed, it was reviewed by the Vibration Analysis group.

Reference - [Finn86]

2.2 Operational Prototypes

Operational prototypes are also a subset of operational expert systems. In general, these systems are complete and usable, but lack the verification by practicing engineers. They are usually developed by Universities and reflect the more academic approach. They should not be underestimated, however; many are more complex than those deemed commercial. They differ only in not being verified for use in practice, though many are quite suitable for commercial use.

2.2.1 Material Related Operational Prototypes

No expert systems currently exist in this area.

2.2.2 Analysis Related Operational Prototypes

2.2.2.1 SACON - Expert System For Operating An Analysis Program

General Description - The SACON expert system, one of the first of the expert systems, provides expertise in the use and operation of the general purpose MARC structural analysis program. Typically it took one year to learn how to use MARC and all its options. SACON drastically reduced that time. Based upon a description, the system recommends a modeling and analysis strategy.

Methodology - SACON is a backward chaining production rule system. It was built at Stanford University using the EMYCIN shell (extracted from the MYCIN effort). The system consists of 170 rules and contains explanation facilities like that of the MYCIN system. The intended audience was non-expert structural engineers. The system took approximately 1/2 day per rule to develop with a total development time of six months.

Reference - [Bennett78, Fenves81]

2.2.2.2 SPERIL-I, Seismic Damage Analysis

General Description - Following strong motion earthquakes, buildings must be analyzed to determine the extent of damage. More specifically, a decision must be made whether to repair the structure or to destroy it. A number of different testing techniques exist along with varying approaches to interpreting visible damage in conjunction with measurements about the earthquake. SPERIL-I attempts to aid the engineer with interpretation and decision making.

Methodology - SPERIL-I was developed at Purdue University. While a number of approaches were considered, particularly pertaining to fuzzy sets and fuzzy reasoning. The basic approach is backward chaining diagnosis written in C. It is known and admitted by the authors that SPERIL-I had significantly reduced the scope of the problem from "too complex real-world problems" to a limited subset. (See also the description for SPERIL-II)

Reference - [Ishizuka82, Fu84, Yao84]

2.2.2.3 SPERIL-II, Seismic Damage Analysis

General Description - Following strong motions earthquakes, buildings must be analyzed to determine the extent of damage. More specifically, a decision must be made whether to repair the structure or to destroy it. A number of different testing techniques exist along with varying approaches to interpreting visible damage in conjunction with measurements about the earthquake. SPERIL-II, an advanced version of SPERIL-I, aids the engineer with interpretation and decision making.

Methodology - SPERIL-II was expanded from SPERIL-I by joint venture between Purdue University and the firm of Wiss, Janey, Elstner and Associates. Inexact inference is used that is based on fuzzy sets for imprecise data and a rule for combining fuzzy sets with certainty factors. Metarules are used to control the inference order and improve the effectiveness and reliability of the results. Some use of predicate calculus is employed.

Reference - [Furuta85, Fu84, Yao84, and Ishizuka82]

2.2.3 Code Checking Related Operational Systems

No systems were found in this area.

2.2.4 Structural Systems Related Operational Systems

2.2.4.1 BDES, Bridge Design System

General Description - BDES, an acronym for Bridge DEsign System, designs the superstructures of short to medium span bridges.

Methodology - BDES is developed by J. Welch of Duke University. The system uses a forward chaining production rule configuration type approach with heavy use of graphics for both input and output functions. The intended user is a novice engineer with expertise for the system supplied by experienced bridge engineers.

Reference - [Welch86]

2.2.4.2 HI-RISE, Design System For High Rise Building

General Description - HI-RISE is intended to perform preliminary structural design of high rise building by generating feasible alternatives to 1) the lateral load resisting system, and 2) the gravity load resisting system. Of equal importance to its function, HI-RISE is the flag ship program of a number of expert systems for building design developed at Carnegie-Mellon University.

Methodology - HI-RISE was developed by M.L.Maher at Carnegie-Mellon University as a Ph.D. dissertation. It was developed using the PSRL language running on a DEC VAX system. The system consists of approximately 300 rules and took about 30 man-months to complete the first version. A graphical interfaces is provided.

It functions as an assistant doing configuration based reasoning. Design information is represented in a network of schemas (or frames). The two load resisting systems are generated using a synthesize, analyze, evaluate paradigm within the context of hierarchial planning. Approximate analysis is used to determine feasibility of the alternative, which is then heuristically rated for comparison with other alternatives.

Expertise for the program was extracted from textbooks on the subject. It is noted by the author that HI-RISE is only a starting point and not a finished project. Its purpose was to serve as a vehicle for learning about the concepts, formalisms and tools need for a large heuristic problem such as preliminary design. Some heuristic constraints were excluded to control problem size, and some engineers would argue that these constraints are those which reflect the real world. No verification with human expert was obtained. Execution speed was extremely slow. It should be noted that many of these limitations have been addressed by subsequent efforts at Carnegie-Mellon University.

Reference - [Maher84, Maher86a, Maher86b, Fenves81]

2.2.4.3 LOW-RISE, Design System For Low Rise Industrial Buildings

General Description - LOW-RISE aids in structural planning, preliminary design and evaluation of industrial type buildings. Planning consists of determining the components of the gravity and lateral load systems of various alternative schemes and of configuring framing layouts that satisfy user input spatial constraints. Like HI-RISE, the alternative are eventually ranked heuristically for comparison with other alternatives.

Methodology - LOW-RISE was developed by G. Camacho as a Master's thesis at Carnegie-Mellon University. It was implemented in a combination of OPS5, LISP, and C. Heuristic knowledge, including generation of framing schemes and layouts for components of the gravity and lateral load systems, were written in OPS5. More algorithmic parts, such as analysis, were coded in LISP. C was used for database work.

The system is a configuration approach using primarily OPS5 production rules. Approximately 240 rules are employed, taking 7 man-months to complete. No graphical interface is employed.

Expertise was supplied by M. Mayo of the C-MU Architecture Department, L. Beech of Beech Industries, W. Reese and R. [illegible] of Salvucci Engineering Inc., and T. Mueskes of American Bridge Company.

Reference - [Camacho85]

2.2.4.4 ALL-RISE, Design System For Preliminary Design

General Description - ALL-RISE is a successor to HI-RISE that retains the fixed grid and hierarchial approach to preliminary design. It encompasses more building types and can design either the lateral or the gravity resisting load systems first.

Methodology - ALL-RISE is programmed in SRL. It focuses attention on one or the other of the structural systems and proceeds in a depth-first manner. When an interaction constraint involving the other system occurs, the constraint is noted but not acted upon. Only upon completion of the first system is the second system considered. Plausible designs for the second system which do not meet posted constraints are eliminated.

Reference - [Maher86b, Sriram86]

2.2.4.5 FLODER, Design System For Floor Framing Planning

General Description - FLODER generates, analyses, and evaluates floor framing plans for a given architecture. Rankings for various alternatives are provided through a heuristic approach.

Methodology - FLODER was developed by A.G.Karakatsanis as a Master's thesis. It was intended to focus upon a particular aspect of HI-RISE, yet the system can stand alone. The system is implemented in OPS5 and LISP, where the primary representations are in OPS5 and algorithmic approaches are coded in LISP. The machine for implementation was a VAX with IRIS graphics support. The expert system approach provides ranking for a number of designs. Graphical output is used extensively.

Expertise was derived from literature only. No verification with human experts was described.

Reference - [Karakatsanis85]

2.2.4.6 HI-COST, Cost Estimating System For Preliminary Design

General Description - HI-COST is designed to be a post-processor to HI-RISE providing cost estimates from preliminary design alternatives.

Methodology - Given the topology and geometry of a building and the preliminary choice by the HI-RISE program, HI-COST produces an estimate of the building's materials' cost. The system is implemented in PRSL productions rules with algorithmic steps programmed in LISP. C is used to interface between LISP and an INGRES database. Total estimates are computed from aggregate subsystem costs as provided by the decomposition used by HI-RISE.

Reference - [Howard83, Rehak85]

2.2.5 Miscellaneous- Safety Related Operational System

2.2.5.1 HOWSAFE, Safety Analysis System

General Description - HOWSAFE analyses personnel procedures regarding a construction firm's safety consciousness. Note that this is a social evaluation, not a physical evaluation. While this system clearly overlaps with the chapter on Construction Expert Systems, many structural engineers are required to monitor and are responsible for safety consideration during the construction of a building; thus, it is included in this chapter.

Methodology - HOWSAFE is a diagnostic evaluation system focusing on finding a social safety rating for a firm. Research on safety have shown attitudes to play a major role in providing a safe environment for workers. Tutorial segments are also included in the program.

The system is implemented using a commercial expert system shell called DECIDING FACTOR and runs on an IBM-PC class machine. Extensive use of certainty factors and combining certainty (and uncertainty) are provided by the shell and are used by HOWSAFE. Explanation features are also provided. Expertise on construction safety was provided by the system author: R. Levitt of Stanford University. A related product, SAFEQUAL has also been developed to aid in selecting safe contractors; it was also developed with DECIDING FACTOR.

Reference - [Levitt86]

3 DEVELOPMENTAL EXPERT SYSTEMS

Developmental expert systems are those: 1) lacking sufficient expertise to be commercially usage, 2) lacking practical commercial value at this time, 3) dealing with more global issues and intended to serve as models for later system development, or 4) lacking adequate user interface to be considered operational (e.g., those that require programming in a particular language to make them work). Developmental expert systems have been included because many will become the next generation of commercial expert systems, and because they provide insight into the future technology approaches.

Many of the descriptions contained in this section are brief. Generally, information for these types of expert systems are sparse and sketchy. Often, the information contained is proprietary and cannot be released. Please seek additional information from system developers if needed.

3.1 Demonstration Prototypes

Demonstration prototypes are a subcategory of developmental expert systems. These systems are operable, but contain only a subset of the knowledge (or expertise) necessary to be a usable system. Sometimes they were developed to demonstrate a concept or to sell a research proposal. Other times the systems are initial prototypes where additional information is being added to complete the system. These systems are important as many are currently being expanded to become operational prototypes and eventually commercial systems. Others are important because they contain the state-of-the-art strategies which will become standard practice in a few years, including exposing a number of new shells and development languages.

3.1.1 Material Related Demonstration Prototypes

No expert systems were found in this area.

3.1.2 Analysis Related Demonstration Prototypes

3.1.2.1 Concrete Structures Under Severe Load

General Description - The analysis of hardened facilities (e.g., bomb shelters) under severe loading conditions generally requires expensive finite element codes. The prototype system developed demonstrates a hierarchy that can be used to build a complete expert system to reduce analysis costs.

Methodology - The expert system approach has been developed by T. Krauthammer of the University of Minnesota. The approach is to decompose the problem into a tree representation and allow the user to progress from known information to both more detail and more generalization. Though the basic problem is to be divided into loading from nuclear environments and explosive assaults, the real focus seems to be on predicting post event behavior.

Reference - [Krauthammer86]

3.1.2.2 FACS, Finite Element Guide

General Description - FACS, an acronym for Flexible Automated Conversion System, is an expert system for guiding the creation of useful airframe models for finite element analysis.

Methodology - FACS is being developed by B. Gregory and M. Shephard at Rensselaer Polytechnic University. The basic approach is to combine the current computer-aided drafting and modeling system with rule based expert systems to build a guide for creating airframe models. Due to complexity, designers are often dealing with only a small segment of the total airframe and conversion of real geometry to finite element modeling often fails to capture essential behaviors.

FACS is a forward and backward chaining classification system. It is written in a combination of PL/1 and PRISM for use on an IBM Mainframe running VM/CMS.

Reference - [Gregory86]

3.1.2.3 CDA, Composite Design Assistant System

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General Description - CDA, an acronym for Composite Design Assistant, is a prototype expert system for aerospace structural engineering. Primary emphasis is on sandwich panel design.

Methodology - CDA was developed by J. Zumsteg at Lockheed Missiles and Space Company. The system is PROLOG based and functions in a backward chaining mode. Using rules about sandwich panel design and analysis, the system assists the engineer during design by coordinating access to a database manager for material properties, and to a laminate analysis code for computations of elastic properties.

Reference - [Zumsteg85]

3.1.3 Code Related Developmental Prototype Systems

3.1.3.1 AASHTO Bridge Rating System

General Description - The expert system aids the structural engineer in carrying out an AASHTO bridge rating by serving as an expert interface between databases and finite element codes. Of particular interest are determining the effects of vehicles and overloaded vehicles on simple span bridges with reinforced concrete decks and prestressed concrete I-beams.

Methodology - The bridge rating expert system was created by C.Kostem at Lehigh University. The system is a forward chaining strategy implemented in FORTRAN and intended to run on CDC machines. The source of expertise was the author. A more complete system is under development.

Reference - [Kostem86a]

3.1.3.2 AMUBC, Australian Building Code System

General Description - AMUBC, an acronym for Australian Model Uniform Building Code, is a small prototype shell (or language environment that is designed to process building codes in general and the Australian building code specifically. The approach is based upon the premise that great expertise exists within the building codes, both empirical and derived from first principles.

Methodology - Processing building codes using a computer is not a new concept. Using the building codes as a source of expertise is not new; that was why they were created. Using expert system technology to implement the code is new. It will allow quicker development cycle, be more readable and hence more checkable, modifications as the code changes will be easier, and personalized extension will be easy to add. AMUBC system is an implementation of a very limited set of the Australian building code using PROLOG operating under MS-DOS on an IBM-PC class machine. Claims to natural language processing are made, but not fully substantiated. Primarily this is a demonstration prototype using production rules to represent the various clauses of the building code. The complete system requires 40K bytes to operate, and explanation facilities are included.

Reference - [Rosenman85, Rosenman86]

3.1.4 Structural System Developmental Prototypes

3.1.4.1 DESTINY An Integrated Design System

General Description - DESTINY, an acronym for Integrated Structural Design, is a conceptual design of an integrated design environment.

Methodology - The system was developed by D. Sriram as a part of a Ph.D. dissertation at Carnegie-Mellon University. It consists of a number of knowledge modules which communicate using a blackboard approach. The four modules are: 1) strategy knowledge modules which analyze the current design state and determine the next action, 2) activation knowledge modules which invoke the appropriate specialist knowledge module, 3) specialist knowledge modules which perform one subtask and are similar to the previous expert systems developed at C-MU, and 4) resource knowledge modules which provide the knowledge base and algorithmic processors required for design and analysis, such as finite element analysis.

Reference - [Rehak85, Camacho85]

3.1.4.2 AIRCYL, Air Cylinder Design System

General Description - AIRCYL, an acronym for AIR cylinder design system, is used to configure and design pressurized air cylinders.

Methodology - AIRCYL was written by D.C. Brown at Rutgers University,and is a configuration type program. It is only a borderline expert system being mostly a simple conventional design program but written in LISP (actually ELISP) running on a DEC System 20 machine. It does contain an explain or traceback feature. Expertise is being supplied by the Accuray Corporation.

Reference - [Brown86]

3.1.4.3 PROSCODE II, Motion Mechanism Expert System

General Description - PROSCODE-II aids in choosing the proper motion mechanism based upon concepts such as support, drive, directional characteristics, and precision required.

Methodology - PROSCODE-II was developed primarily to demonstrate the methodology. The system is a rule based forward chaining mechanism. It is written in PASCAL running under the UNIX system for a VAX machine. The system provides simple user interfaces and reasons with a limited level of uncertainty. Rules that are used to reach a conclusion are logged and available at the end of a run. The motion selection system consists of approximately 70 rules. The author of the program, T. Tomiyama of University of Tokyo acknowledges very slow response: approximately 70 rules require 6 seconds to execute; acceptable currently, but a potential problem with future expansion.

Reference - [Tomiyama85]

3.1.4.4 TOPOLOGY-I, Topology Inference Mechanism

General Description - TOPOLOGY-I is used to aid and examine topological relations between general objects.

Methodology - TOPOLOGY-I is a simple reasoning system used primarily to explore an approach to specifying and reasoning about topological relationships between objects. It is rule-based and written in PROLOG. No real user interface exists; operation requires the user to program in PROLOG.

Reference - [Gero85c]

3.1.5 Miscellaneous - Teaching Related Demonstration Prototypes

3.1.5.1 ICAI Moment Instructional Program

General Description - ICAI, an acronym for Intelligent Computer Aided Instructions is a tutoring and advisory system on moments and deflections in structures. That is, the system critiques proposed solutions input by students.

Methodology - ICAI-Moments is implemented using a shell called GEPSE, a forward chaining rule based expert system shell written in C and operating on IBM-PC class machines and UNIX based machines. Rules are written using the ONL language with a LISP-like syntax. The rules are used to determine qualitative answers, not quantitative, with the intent of inducing a better understanding of the mechanism of moment-deflection relations without concern about the mechanics of computing the results.

Reference - [Slater86]

3.2 Systems Under Development

Systems under development comprise the remainder of developmental expert systems. Systems which have been proposed are included here provided that actual writing is underway and completion is anticipated. Systems which are only proposed (not being written) are not included. This sections is, of course, the most incomplete. No clearing house for communicating projects underway exists in any formal sense.

3.2.1 Material Related Systems Under Development

No systems were found in this area.

3.2.2 Structural Analysis Related Systems Under Development

No systems were found in this area.

3.2.3 Code Related Systems Under Development

No systems were found in this area.

3.2.4 Design Systems Under Development

3.2.4.1 Preliminary Structural Design System Under Development

General Description - The system under development will focus on mid-height steel frame buildings. When completed it will advise users on the selection of a proper structural system, column spacing, member sizes, and interstory drift ratios.

Methodology - The system was originally to be developed in an EMYCIN environment on a DECsystem 20. This has been changed to use the commercial expert shell called EXSYS running on an IBM-PC-AT.

The knowledge base is being constructed from written technical facts, and interviews with practicing structural engineers. Emphasis is being place on ten to thirty story steel frame buildings. Certainty factors are being used and explanation features will be available. The work is being done by F. Naeim and J. Martin of J.A. Martin & Associates of Los Angeles, California.

Reference - [Naeim86]

3.2.4.2 CAESE, Integrated Software Environment

General Description - CAESE, an acronym for Computer Aided Engineering Software Environment, is a collection of systems and tools creating a conceptual architecture for software development

Methodology - An initial version of the architecture was developed in 1981 by Dan Rehak of Carnegie-Mellon University. Constant work progresses on extending and revising the initial design and on building prototype components of such a system. The system is to include components for project planning; conceptual synthesis including layout generation, cost analysis, functional planning, element design, and preliminary design document production; detailed synthesis; review; and construction.

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Reference - [Rehak85]

4 CONCLUSIONS

4.1 Only Good Starts

Expert systems are a relatively new technology, emerging as a practical approach approximately three years ago. Many good projects have been started and feasibility of the technology for many applications have been clearly established. Very little is really ready for use by the structural engineer and several more years will probably be required before commercial grade expert systems are abundant. As with any new technology, there is some misuse caused mostly by misunderstanding and the need to experiment. Some of the work being presented under the title of "expert systems" is shear wishful thinking or outright charlotenism. This is inevitable with any new technology receiving great attention, but most efforts are sincere. Of primary concern to myself are the sincere efforts that are failing: often miserably, and other times simply missing opportunities to be better.

4.2 Incompleteness Abounds

Most expert systems presented here are too incomplete to be ready for actual use in practice, yet there are several ways in which they are incomplete.

First, many systems simply were not done in a professional manner. The same engineers who would have had reams of plans, schedules, and other materials when designing a structure; failed to plan the development of their expert system (a system which is by the author's own admission is more complex than a single building design). " Artificial intelligence" and "expert systems" are techniques; and most conventional planning and design approaches can be used with these new techniques.

Second, testing of most systems is severely lacking. Any program to be used in commercial practice must be correct to every extent possible. This includes limiting input to reasonable values, checking cases at boundaries of the domain, testing special cases where strange behavior may occur, and running sweeping tests (groups of test cases examining a range of one input value to assure consistent trends in output). Few programs can ever be assured to 100 percent that operation will be correct, and expert systems make the task more difficult. Testing is time consuming and expensive (PUMP-PRO required 50 percent of its development time to do testing), but TESTING IS ESSENTIAL and often overlooked in expert system development.

Third, expert systems must contain expertise. While textbooks can provide an important and valuable source of information which should be incorporated into the system; textbooks are insufficient by themselves. Human expertise must be consulted: either at the time of creation, or at the time of testing. Without the heuristic knowledge (rarely contained in books) the system will not reflect the real world, and thus, will not perform well in the real world. It should also be noted that there are a few developers who can serve as the expert, but not nearly as many as are developing expert systems under that assumption.

Fourth, most systems are built around a particular shell whether that shell is appropriate to the solution or not. The development of more commercial shells and the natural maturing of the technology will reduce the magnitude of this problem. The current approach of using the shell most readily available has led many systems to size limitations, complexity limitations, awkward representations, inadequate user interfaces (a point far more important for real world use than given credit for), and slow system response times. Attention to what some expert system developers have sloughed off as "details" will ultimately make or break the use of expert systems in routine commercial practice.

Fifth, many of the topics chosen for expert systems are simply too large or even completely unbounded. This is particularly true of some university research. Design as a whole is not well understood by humans, it seems unlikely that anyone will build a system to accomplish it. It is not impossible, however, and there lies the difficulty; many people play lotteries under the same illusion and a few do win. A more reasonable approach might be to build the pieces first (see below).

4.3 Unfulfilled Potentials

There are several sections within this chapter that have no expert systems associated with them. It is equally important to remember that I only used the top level of decomposition; had the complete categorization been used, even more areas would have been void. It is hoped that this report will stimulate some interest to fill in those voids; but remember that even those which are filled, still have many unexplored systems in them.

Part of the reason for voids in some areas and apparent duplication in others is because no forum exists for describing what research and development is on-going. The nature of this forum could take several avenues from a newsletter, to an electronic bulletin board (one does exist for construction related systems), to a journal (several are beginning to appear), to even sponsored research centers.

Very few organizations, or individuals for that matter, have developed a strategy for building a family of expert systems, though most acknowledge that they intend to build several. In this oversight, two key opportunities are missed: 1) the chance to learn and to use what is learned while building the first system, in the creation of the second system, and 2) the chance to combine the individual efforts to create a higher level expert system. The latter is quite simple for many shells, it only requires that the rules be combined with a text editor and fed to the expert system shell.

4.4 Incorrect Audience

Perhaps the biggest error being made in expert system development is lack of consideration for expected audience. Most systems do not consider the knowledge level of their intended audience; tutorial sections of programs are lacking; explanation features are incomplete; and terminology is usually undefined. Even more incomprehensible is that expert system developers sometimes fail to determine even IF there is an audience. They blindly create expert systems for which no one has any use. Universities are notorious for this problem for they lack an appreciation of what are the real problems facing practicing engineers. Communication by both parties can solve this problem, but joint ventures where both problem definition and expertise can flow would be even better.

4.5 Final Conclusions

Despite the negative points just made, I am optimistic about the future of expert systems. I am optimistic not just because I create them, but because they will solve problems that could not be handled before. As the technology becomes more mundane and common place, it will become a technique for solving problems instead of the present technology seeking a problem. As the techniques become available to industry, the solutions will become less ambitious, more practical, and very much in demand. Many good systems have been built and are being built.

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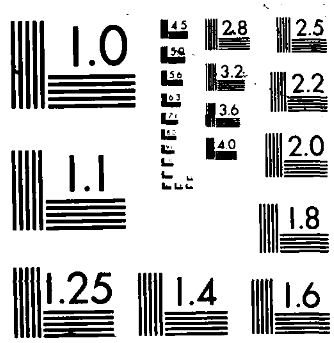

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Chapter Four
Expert Systems in Geotechnical and Environmental Engineering

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Chapter 4

Expert Systems in Geotechnical and Environmental Engineering

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1. Introduction

This chapter presents a review of some applications of expert system technology to problems in geotechnical and environmental engineering. The chapter is organized into two main sections, one for operational systems, and a second one for developmental systems. For each system, a short summary is included that discusses the domain of interest and implementation details.

1.1. Description of Geotechnical and Environmental Engineering

Geotechnical engineering is a term that has come to be used for the areas of soil mechanics and foundation engineering, in addition to geological engineering and related topics. The field of geotechnical engineering is concerned with the following topics:

- study of the earth as a structural material;
- measurement of properties insitu, i.e., strengtl, compressibility, permeability;
- measurement of properties in the laboratory, classification, shear strength, compressibility, permeability, etc.;
- design of both shallow and deep foundations for supporting building and structure loads;
- design of earth structures (e.g., dams) and earth retaining structures (e.g., retaining walls);
- stability analyses of both manmade and natural slopes;
- control of the placement of soil, and techniques for improving soil properties (e.g., compaction);
- determination of stable depths of, and techniques for, the excavation of soil.

Environmental Engineering in its broadest context refers to many topics and for the purposes of this discussion is divided into the following areas: 1) hazardous waste, 2) waste water treatment, and 3) water resource management. Hazardous waste issues are quickly becoming a topic of concern for both the engineering community and the public at-large. Some of the issues in hazardous waste include:

- design of waste storage facilities;
- design of waste incineration and disposal plants;
- identification and classification of waste products;
- cleanup and securing of hazardous waste sites;
- mitigating health hazards related to waste products.

Waste water treatment problems differ from hazardous waste problems because the municipal waste water from residential, commercial, and industrial users is not considered as hazardous as the chemical contaminants that are encountered in many *hazardous* waste sites. Also, these byproducts are usually produced and collected under much more controlled circumstances than is usually found with the hazardous waste problem. Some of the issues of include:

- collection, treatment, and distribution of industrial and residential waste water treatment;
- design and maintenance of facilities, including waste water treatment plants, collection systems including sewer facilities and piping networks;
- appropriate treatment for the different types of wastes, how to maintain facilities, what level of treatment is necessary, and the potential use of the treated water.

Water resource management is concerned with the control, protection, and management of water supplies. This includes:

- management of municipal water supply treatment facilities;
- management of reservoir facilities, including discharge quantities, and maintenance of reservoir levels;
- estimation of flood potential, and the necessary precautions to be taken in the event of flooding.

1.2. Motivation for using Expert Systems

Expert System technology has significant potential for application in the area of geotechnical engineering. Many of the design procedures presently in use in this engineering discipline are based on empirical rules that require an engineer to have gained years of experience before they can be used effectively. Problems in this domain often must deal with uncertain and unreliable data concerning soil properties and loading conditions. Algorithmic programs require that the user provides a complete problem definition before a solution of the problem can be developed. In geotechnical engineering this can be a difficult task due to the problem of providing a complete description of a material that is as inhomogeneous as soil. Also, although algorithmic programs are efficient at making large numerical computations, the design process in geotechnical engineering often involves tasks other than just numerical calculations. The judgment of experts, based on years of experience, must be incorporated into the design process so that decisions can be made taking into account site conditions that are often ill-defined or heuristic in nature. These are the type of tasks that are most efficiently handled using knowledge-based expert system techniques.

Environmental engineering experiences many of the same problems that complicate geotechnical engineering. The problem of handling uncertain and incomplete data again is one that is not easily accomplished using traditional algorithmic solutions. Many of the applications discussed in this section deal with environmental system controls and design. These types of system control problems, e.g., diagnostics of a waste incineration facility, involve much more than numerical computations. For the waste incineration facility, proper diagnosis is dependent on both quantitative and qualitative data. The expertise of the operator(s) often is the critical link in formulating and implementing proper solutions to a problem. It is these types of problems in which conventional programming methods are intractable that

have new potential using knowledge-based expert system techniques.

2. Operational Systems

In this section, summaries of expert systems that are presently operational are presented. The section is divided into two sections, one for commercially available systems, another for prototype systems.

2.1. Commercial Expert Systems

There were no references found for any commercial systems found for either geotechnical or environmental engineering.

2.2. Operational Prototypes

The expert systems presented in this section are considered to be operational prototypes. In the following sections operational prototypes are discussed, first for geotechnical engineering and then for environmental engineering. An expert system is presented through a discussion of the objectives and goals, the methodology and implementation, and finally, the current state of the project.

2.2.1. Geotechnical Engineering

Four operational prototype expert systems are presented in this section: two are concerned with the interpretation of data for the evaluation of subsurface conditions and two deal with design problems.

2.2.1.1. CONE

Introduction. CONE is a knowledge-based expert system that has two main objectives: 1) to classify soils based on cone penetrometer data, and 2) to infer soil shear strength from this same data. The raw input data that is processed by this system comes from a conically-tipped penetration device that is either electrically or hydraulically pushed into a soil profile. As this device penetrates the soil, the tip resistance and the frictional resistance along the side are measured continuously with depth. This data can then be used for making soil classifications, estimating soil shear strength, and often can be directly used for pile capacity determination for a particular soil profile.

This system performs a series of tasks, starting with preliminary information gathering concerning site details and log parameters and raw data input. This raw data is then checked for validity and reasonableness and further preprocessed for use in the remaining sub-tasks. In the two main sub-tasks, soil classification and inference of shear strength, expertise from multiple sources is used to produce the desired end results or values.

Methodology. The knowledge incorporated into CONE is embodied in a series of production rules using the OPS5 programing language. Because the sub-tasks of the system also require the performance of procedural tasks (e.g., pulling values from graphs), a series of LISP functions are accessed from the OPS5 production rules.

The knowledge base is organized according to three processes: information gathering, soil

classification, and shear strength estimation. The control strategies, goal driven and data driven, are implemented by creating and satisfying goals. The information gathering process uses a goal driven strategy and the soil classification and shear strength estimation uses a data driven strategy.

Cone uses fuzzy logic to combine the analytical results of multiple experts, to represent confidence, and to provide a common representation for natural language attributes. The basis of fuzzy logic is fuzzy sets which composed of several elements along with their associated degree of membership. A fuzzy set, for example, is used to represent soil classification, e.g., for a clay soil with zero degree of membership in sand or silt the fuzzy set would be { 0.0|sand, 0.0|silt,1.0|clay}. The results of multiple experts are stored in distinct fuzzy sets which are then averaged to produce a single result. Averaging is accomplished using a fuzzy weighted average that incorporates both the belief and the corresponding weight associated with each factor.

Current State of Project. This system was carried to the prototype stage where it was tested against several published soil stratigraphy examples. The system was found to be fairly reliable, giving results in the range of 80% accuracy compared with the published results. Progress on the system was stopped at this stage and no further development has occurred.

Reference: [10]

2.2.1.2. RETWALL

Introduction . When faced with an earth retention problem, a designer has a wide choice of retaining wall types that may be used. The decision as to which type of wall is most appropriate for a particular situation depends on several factors, including wall height, soil conditions, and the location of the wall. While there is an abundance of documentation available on design and construction details for each particular wall type, very little documentation exists on which wall type is better for a particular situation. Instead, the designer must draw upon his own experience and expertise when making this decision.

RETWALL was developed to specifically address this problem of choosing applicable wall types. The user is required to input geometric descriptions of the wall constraints and corresponding soil properties. Based on this information and the information stored in the knowledge base, the system first evaluates whether or not a wall is required to solve the problem. If a wall is necessary, the system then evaluates which of the wall types that it knows about can be successfully applied to the problem.

In addition to recommending a particular wall type, the system also has the capability to perform the actual design for blockwork walls. Included in this design function is the ability to produce design drawings that can be used for wall construction.

Methodology. The RETWALL system was developed using an expert system shell called BUILD. This shell provides the control structure for the overall system. BUILD consists of a series of production rules that provide both goal driven and data driven control, in addition to an explanation facility. The system queries the user by stepping through the rules in a sequential manner. The knowledge in the system is represented as a series of production rules that exist in a separate module that is accessed by the BUILD

shell. The sequential operation of the shell was taken advantage of to obtain a second level of control within the knowledge base. For most problem descriptions, several wall types may be applicable. By placing the rules in the knowledge base in an order that reflects the expert's preference of wall types, the system bases its recommendations on the first wall type it finds that is considered acceptable.

Current State of Project. In its present state, RETWALL is able to make a choice between approximately 10 available wall types. Additionally, if the recommended wall type is blockwork, the system will carry out the actual wall design and provide the user with a set of construction drawings.

Reference: [3]

2.2.1.3. Shallow Trenches

Introduction. Shallow trenches, defined as those less than 24 feet deep, are typically excavated for the placement of underground utilities. These trenches continue for long distances and therefore often encounter a large variety of soil conditions. The choice as to what safety precaution will be used for a trench, e.g., sloping or bracing, depends on the soil conditions and the job foreman must make decisions on-the-spot as excavation proceeds. The consequences of a cave-in failure often become fatal to workers trapped in the trench at the time of collapse.

The National Bureau of Standards (NBS) has recently developed two new soil classification systems to be used during excavation that are intended to increase the safety of this type of excavation. With these new classifications, the job foreman, who is usually not a soil expert, can plan safety precautions for the soils encountered by drawing upon the expertise of the developers of the classification systems. A knowledge based expert system has been developed for providing assistance to the job foreman in properly using and interpreting the new systems.

Methodology. The shallow trench system has been developed using an expert system environment, Personal Consultant, developed by Texas Instruments for use on personal computers. The knowledge base consists of parameters which store factual data and production rules that represent the heuristics for manipulating the data. Personal Consultant provides an inference mechanism that uses backward chaining to reach conclusions. This environment also provides an explanation facility that can be accessed by the user to question the system about how and why an action was taken or a conclusion was reached.

The knowledge base consists of two main sections or contexts which allow repetitive consultations without exiting from the system. There are three other contexts that then handle the tasks of: soil classification, design parameter inference, and trench bracing design.

Current State of Project. At the completion of this thesis, the system was capable of completing the soil classification using the NBS systems, and the design parameter inference task is fully operational. The trench support design task is not operational, due partly to time constraints and partly due to problems with implementing a larger problem in the present environment.

Reference: [6]

2.2.1.4. SOILCON

Introduction. One of the first tasks in building a new structure is to evaluate the subsurface conditions in anticipation of foundation design. The level of geotechnical investigation required will depend on several issues, including details of the structure and the present level of knowledge available. A prototype system for matching the requirements of a proposed structure with the level of information known about a site and the required amount of information has been developed. The goal of the system is to advise the user on how much investigation is necessary to reduce the chance of risk involved with the subsurface to an acceptable level. It is the intention of the system to work as a project management tool for interfacing between the owner and the contractor in deciding levels of geotechnical investigation necessary.

Methodology. This prototype system was developed using the M.1 expert system shell. This commercially available environment provides a backward chaining control strategy that interfaces with a production rule knowledge base. This system contains a knowledge base that contains the information about various structure types. For example, if the structure under consideration is a one-story building that does not require deep foundations then the system can match this requirement with the desired amount of subsurface information for reducing the risk to an acceptable level.

Current State of Project. The subsurface risk system has been developed to the point of being a prototype system. There were two main goals that were attained during the development of the prototype. One was to gain a better understanding of the M.1 environment and expert system technology in general. An secondly, to better understand the problem domain of subsurface risk and its relation to project requirements.

Reference: [13]

2.2.2. Environmental Engineering

The systems to be presented in this section will be further divided into the areas of hazardous waste, waste water treatment, and water resource management.

Hazardous Waste

The first series of systems deal with the problem of hazardous wastes. This area has provided the most abundant list of environmental engineering related operational systems.

2.2.2.1. PVC Liner

Introduction. An expert system has been developed for evaluating the use of PVC liners for the containment of hazardous wastes. The goal of this system is to use results from short term immersion tests on liner materials to project possible incompatibilities between the liner and the waste to be contained. There are no established rules for how these tests should be interpreted or their applicability towards long term behavior of the liner. Therefore it is necessary to use the judgment of an experienced

person familiar with the conditions.

Methodology. The authors use a *production system* approach to implement the solution. This consists of a collection of classification rules and scoring procedures for turning observations (immersion test results) into conclusions (likelyhood of chemical incompatibility). In this production system there are three main components: 1) a set of rules, 2) a data base, and 3) a control system. A fourth element in this system is that of inexact reasoning. Within the system a certainty factor is associated with each resulting inference based on the belief of the propositions leading to that inference. The overall certainty factor is equated to the belief in the most prominent premise.

Current State of Project. At the time of publication the system had been tested against a set of immersion test results for a particular liner material and gave recommendations that were compatible with the expert's opinion.

Reference: [12]

2.2.2.2. GEOTOX

Introduction. GEOTOX is an knowledge-based expert system developed to aid in the assessment and evaluation of hazardous waste sites. The evaluation process is an important but complicated step in determining the priority of the site. This evaluation process is complicated by the usually limited amount of data available and often requires the combined expertise of several areas including toxicology, chemistry, mineralogy, and environmental engineering. Presently there are several qualitative models available for assigning a priority to a site that are in use by the EPA.

The present system attempts to bridge the gap that often occurs in site evaluation caused by having only one evaluator at a site that requires expertise in multiple disciplines. Initially the system obtains input volunteered by the user using key words contained in GEOTOX's knowledge base. This information is then used to update a priority list of characteristics required for assessment. Based on these priorities the system then queries the user for further information needed for the assessment.

Methodology. A framework for the system has been developed and for the present system contains: a) a rule base; b) domain related data bases; c) an inference mechanism; d) a user interface; and e) a problem specific data base.

The knowledge base which provides the expertise for GEOTOX consists of a series of production rules written in PROLOG. Then, for each site characteristic, there is a corresponding set of rules that define its contribution to the overall site hazard. The contribution of each characteristic consists of two values: **h**, which represents a hazard value; and **c**, which indicates the user's confidence in the data. By using this two value system, GEOTOX can determine the importance of each characteristic to the site assessment by using the weight assigned by the expert (implicit in the value of h) and the confidence assigned by the user (c). This is in contrast to other models which are unable to assign variable weights that can be site specific.

The interface for GEOTOX provides two main facilities: commands and explanations. Commands allow the user to control the flow of the system by volunteering information, changing answers or rules, and asking for deductions. The explanation facilities allow an examination of the current state of the system including the reasoning followed to reach the present state.

Current State of Project. The system has been validated successfully agains other assessment models for two inactive landfill sites. Work is continuing on the system including the interfacing of the system with computer graphics capabilities.

Reference: [14]

2.2.2.3. Waste Incineration

Introduction. As the cost of disposal of hazardous waste continues to increase and further regulations are imposed on their disposal and storage, wastes are now being used as fuel materials. Incineration facilities are now being developed and used in the treatment process that exploit hazardous waste as a fuel. An expert system has been developed for diagnosing malfunctions in hazardous waste incineration facilities.

This system incorporates fuzzy probabilities into a fault tree analysis that is then used to diagnose possible causes to malfunctions in incineration systems. The fault tree is traversed by the system as the user answers a series of goal-driven queries aimed at reaching a conclusion on probable causes to incineration system malfunction(s).

Methodology. A commercially available expert system shell, M.1, was used for the development of this system. The fault tree, provided by the domain expert, is a diagrammatic representation of knowledge about failure modes to incineration systems. This information is transformed into a series of IF-THEN production rules using the M.1 shell. The M.1 shell also provides an inference mechanism that uses a goal-driven or backward chaining control strategy that is perfectly suited for transversing a fault tree analysis.

In conventional fault tree analysis, numerical values must be assigned to the probability of an event occurring and the failure rates of individual system components. In hazardous waste incineration systems it is very difficult, if not impossible, to assign probabilities to hazardous events that have only rarely occurred or may not have ever occurred. To overcome this difficulty, the system uses fuzzy probabilities that are better able to represent the subjective notion of the operator as to the probability of occurrence of an event. Propagation of these fuzzy probabilities to the top event is accomplished through the use of a multiplication operator for the fuzzy sets.

To incorporate the fuzzy probability capabilities into the M.1 environment, additional IF-THEN rules were included in the knowledge base. Two techniques are used for assigning the fuzzy probabilities: 1) the expert system is capable of receiving the probabilities directly from the user, and 2) the values can determined by the system based on the value given for incineration system parameters and the normal range of values for that parameter.

Current State of Project. This system appears to be at the prototype stage, where it has been tested using several malfunction cases. Further development of the methodologies used for the system are encouraged by the developers.

Reference: [2]

2.2.2.4. Inactive Waste Sites

Introduction. One of the first steps in the evaluation of hazardous waste sites is the ranking of the site based on the potential for safety problems or ecological and environmental damage. The Hazard Ranking System (HRS) assigns a numerical value to a site that is then used to rank a site nationally for consideration of federal aid towards remedial action. This ranking uses the Mitre model for determining the site hazard value. Use of the Mitre model is a straightforward process once the site has been properly characterized and documented. It is this characterization and documentation of a site that requires considerable expertise.

The system is intended to provide some of the expertise necessary for site characterization. This system then can help an evaluator characterize a site by emulating the procedures an expert would follow in documenting and characterizing a site as a prelude to using the Mitre model.

Methodology. The representation scheme used in this system includes a knowledge base consisting of a series of production rules written in OPS5. The information contained in the knowledge base attempts to include both the rules and facts that are provided by the HRS system and additionally, the information or rules-of-thumb that an expert would use to characterize a site. All numerical computations were performed using external functions written in COMMON LISP. By attempting to model the problem solving strategy that an expert would use, information that influences an experts' opinion but is not necessarily contained in the HRS system can be included in the characterization process.

The inference engine in OPS5 only supports forward chaining, or data-driven control strategy in this system. To allow for instruction-driven, or backward chaining the production rules were implemented by splitting a goal into subgoals in a recursive manner.

Current State of Project. Currently the system is capable of producing a HRS scoring for a site. An example of this scoring process related to the subgoal of Permeability has been presented in addition to an example showing the system's ability to make numerical computations of groundwater flow direction and gradient based on available site data. This second example represents the type of information that could influence an expert's characterization of a particular site. Development on the system is ongoing with the authors indicating that capabilities in the following areas are planned: more detailed consideration of the nature of the waste including toxicity, consideration of the quality and sensitivity of the data, and an explanation facility for providing a description of the criteria and logic system used to arrive at the final results.

Reference: [7]

2.2.2.5. DEMOTOX

Introduction. The problem of assessing groundwater contamination potential is an important task necessary for planning remedial designs for a hazardous waste site. This problem often has to address chemical mobility in soil systems, in addition to biodegradation and transformation concerns. To handle these problems, the designer must make certain assumptions and estimates based on expert knowledge for quantities, such as partition rates, which relatively few have been measured.

DEMOTOX is a knowledge based expert system developed to aid in the assessment of potential groundwater contamination. The system is centered around a pollutant ranking model which utilizes a mobility and degradation index (MDI). In the calculation of the MDI, the model uses both measured data from a laboratory, and estimations and assumptions based on expert knowledge. The confidence that is associated with measure data by nature is usually higher than the estimates and assumptions of experts. In this system, confidence values are used to modify the MDI to develop a "confidence adjusted" MDI (CAMDI).

Methodology. The core of the DEMOTOX system consists of a pollutant ranking model. This is the model that determines the value of MDI. Then the system incorporates several small data bases that include information on soil texture relations, permeability, organic chemical classification, in addition to confidence factors. The system uses these data bases for calculating confidence factors based on the quality of available data, expert system estimates, and any user input levels. A new, adjusted CAMDI is then calculated corresponding to the generated confidence values.

This is a rule-based system developed using the M.1 expert system tool. Over 200 rules exist, plus greater than 250 facts and numerous *explanation* facilities. The system can answer "why" input is needed, reason about incomplete or missing data, make estimations for input parameters, assign confidence factors, and make decisions based on model outputs.

Current State of Project. Presently, the system is at the demonstration stage. A series of twelve constituents were ranked using this system and compared with a ranking provided by the developers of the DMI system. Although DEMOTOX assigned higher values for potential groundwater contamination, the constituents were ranked using CAMDI in the same order as the original data.

Reference: [9]

Waste Water Treatment

Only one operational prototype system in the area of waste water treatment was found and is presented below.

2.2.2.6. Activated Sludge

Introduction. Activated sludge waste water treatment facilities depend on the knowledge and expertise of the operator for its successful operation and control. In this type of facility, there are two general types of information available to the operator: 1)) quantitative data from instrument readings and laboratory

results; and 2) qualitative data based on observations of the behavior of the system and its parameters. The operator uses his expertise in the form of rules-of-thumb or heuristics to synthesize the data into the formulation of problem solutions.

A prototype expert system has been developed to investigate the usefulness of expert system technology in the operation of waste water treatment facilities. The emphasis of the system is on representing the uncertainties that exist between symptoms, diagnosis, and treatments.

Methodology. The knowledge representation for this expert system requires the ability to allow for uncertainties in the relations between symptoms of process malfunction and diagnosis of casual events, and between causal events and mitigating responses. To allow for these uncertainties, fuzzy relations were chosen to form the basis for the knowledge base. The advice of a process control expert was then used to develop a table of relationship values between symptoms and diagnoses for the detection of toxic substances in the facility influent. When the operator observes abnormal conditions, he assigns values of perceived certainty to each of the observed symptoms. These values comprise a fuzzy set which is then used to resolve which diagnosis is the most certain based on the observed symptoms. When inconsistencies occur, the system uses a negation process to eliminate any impossible diagnoses to resolve the inconsistency and result in a final solution.

Current State of Project.In its current state, the system presently contains a set of possible diagnoses for the detection of toxic substances in the facility influent. Possible further expansion of the system includes an explanation facility and additional and more comprehensive symptom-diagnoses relations.

Reference: [4]

Water Resource Management

Water Resource Management is an area that also appears to be a popular topic for expert systems.

2.2.2.7. Flood Estimation

Introduction. Several standard computational models are available for estimating design floods for civil engineering projects. The design flood is considered to be either a maximum probable flood that may be expected or a flood associated with a specified return period, depending on the structure under consideration. There presently exists conventional computer programs that can be used for making the computations necessary for this type of flood estimation.

Although these computational programs exist, the choice of which model (and consequently which program) is most suitable to a problem is not always apparent. The most appropriate model will depend on the importance of the project, consequences of failure, and availability and quality of data. It is at this stage, where the hydrologists must make a judgment based on their expertise, that an expert system can be very effective in assisting the problem solving.

Methodology. A system has been developed that provides interactive advice about design flood

estimation for floods associated with specified return periods. The first task performed by the system is to classify the problem into one of five categories based on the type and quantity of data available. Once the problem has been classified, the system then proceeds to advise the user as to the most suitable estimation technique for the current problem.

The user consultation begins by giving a description of what assumptions are being used by the solution technique. Then the system invokes appropriate procedures to verify that each of the assumptions have been satisfied before proceeding. At the completion of this verification, the user is notified as to which computational model is most suitable and then provided advise on how to properly use the recommended model. The appropriate external program is then called and run by the system.

The consultation session ends by providing the user with advise on interpretation of the results generated by the program run by the system.

Current State of Project. The present version of the system is capable of categorizing the flood estimation problem, advising which model is most appropriate for the problem, calling and running the appropriate program, and finally, providing advise on interpretation of the resulting output. Further possible additions to the system include interactive graphics procedures to supplement knowledge acquisition and the incorporation of numerical results into the system's line of reasoning, which it is presently unable to do.

Reference: [1]

3. Developmental Expert Systems

In this section a discussion of systems presently under development is presented. The information from this section will comes mainly from the results of the ASCE survey sent out to most US universities and commercial establishments that may be working in the area of knowledge based expert systems. In this survey several investigators indicated pending and current proposals for work that had been started dealing with expert systems. This section is divided into two groups, one representing systems that are presently under development, and a second group of systems that are at the conceptual stage of development.

3.1. In Development Expert Systems

The systems presented below are all systems that are currently in the implementation stage. Considerable work has been done on these systems but they have not been fully implemented and tested.

3.1.1. Geotechnical Engineering

3.1.1.1. SITECHAR

At Carnegie Mellon University a system for site characterization is presently under development. The objectives of this research includes the formalization of the expert rationale and opinion used by engineers and geologists to infer soil stratification, and the development of a prototype expert system that will use a knowledge-base incorporating this formalization for assisting in site characterization. Presently, the formalization of the rationale and opinion is near completion, and the conceptual framework for the prototype system is under development.

Reference: [11]

3.1.2. Environmental Engineering

Hazardous Waste

There are no Hazardous Waste systems presently in development that will be discussed here.

Waste Water Treatment

3.1.2.1. MOUSE

A system has been developed at the Danish Hydraulic Institute for computer aided design of urban sewer systems. The system consists of a series of computational models that use advanced numerical models for design. The use of these models requires a high level of specific knowledge for discretion purposes. An expert module is currently being developed that will allow automation of the discretion and will also guide the user in solving any resulting numerical problems that may arise.

Reference: [8]

Water Resource Management

There are no Water Resource Management systems presently in development to be discussed here.

3.1.2.2. Reservoir Management and Planning

An expert system is currently under development at Georgia Institute of Technology for reservoir management and planning. This is a problem that is characterized by uncertainty and lack of information, and requires the use of subjective judgment and empirical knowledge in the decision making process. Kangari and Rouhani are developing this expert system for assisting in the operators of reservoirs.

There are three main components to the system; the knowledge base, the control system, and the a user interface. The knowledge base is divided into factual knowledge and empirical rules. Algorithmic models, along with physiographic, climatic, and socioeconomic data are considered factual. Expert opinions and rules-of-thumb are embodied in the empirical rules. The control system consists of a knowledge base, a database and algorithmic system processor, and an explanation module. Modeling of

the system performance, input of data, and redirection of the problem solving approach is then accomplished through the user interface.

Reference: [5]

3.2. Conceptual Expert Systems

This section discusses systems that have not reached the implementation stage of development, some of which are still at the proposal stage. There are numerous researchers who have ideas and concepts that could be presented here and the number is continuing to grow as expert system technology become more widely accepted and available. For the sake of brevity, a representative sample of systems and possible applications that researchers are interested in pursuing is presented.

3.2.1. Geotechnical Engineering

In the area of geotechnical engineering, two ASCE survey respondents indicated applications presently being studied:

1. At Tulane university, Assist. Prof. T. Hadj-Hamou indicated work on a system for soil property identification is under development;
2. Dr. S. Leroueil of *Universite' Laval, Cite' Uviversitaire* in Quebec, Canada, indicated that work on an expert system dealing with slope stability is ungoing.

3.2.2. Environmental Engineering

3.2.2.1. Water Treatment Facility

At Syracuse, Dr. S. J. Nix is presently working on the development of an expert system for the operation of a water treatment facility. To date, most of the work has focused on knowledge engineering through interaction with operators for water treatment facilities. The expertise and rules-of-thumb that will comprise the knowledge base are being formalized. It is intended to implement the working system on a TI Explorer using the KEE expert system shell.

In addition to the work at Syracuse, several other investigators indicated interest in the following areas:

1. The University of Maine has a proposal into NSF for the design of an expert system for groundwater modeling;
2. At the University of Alaska it was indicated that a system was under development for use as a front end to a large water resource program in addition to a system(s) for application in laboratory courses.

4. Summary and Conclusions

In this chapter numerous operational and developmental expert systems have been presented covering many different problems in geotechnical and environmental engineering. Despite the seemingly wide variety of topics being approached by expert systems, the systems can be conveniently categorized, by the type of problem being approached or by the programing tools utilized in the development.

One type of problem that is becoming a popular topic for expert systems is the need for intelligent

front-ends to already existing programs or models. FLOOD is one example of this type of system where the objective of the system is to provide a user with advice on which, of several already existing models, is most applicable to the problem under consideration. There is no attempt by FLOOD to incorporate new analytical techniques for flood estimation, instead the objective is to improve the use of existing models and programs. RETWALL also handles a similar problem where the goal is to evaluate what commonly existing retaining wall structure would most likely be the best solution to a particular earth retaining problem. As is the case with FLOOD, this system provides advice to the user and then uses conventional design techniques to complete the problem solution.

Another major application of expert systems consists of classification problems where interpretation of problem parameters has been poorly defined or heuristic in nature. Traditional programming techniques have not been applied very successfully to these problems and instead an expert is usually called upon in these situations. Several systems presented in this chapter fall into this category. Geotechnically characterizing a site based on limited data is an example of this type of problem. This task is traditionally performed by experienced engineers who blend a knowledge of geology with past experience and limited laboratory soil classifications to infer site characteristics. Four different systems, discussed previously, attempt to incorporate this process into an expert system, those being: CONE [10]; Shallow Trench [6]; Subsurface Risk [13]; and site characterization [11]. Hazardous waste site characterization also requires the handling of incomplete, unreliable data as was seen in GEOTOX [14] and Inactive waste sites [7].

Diagnostic problems represent a third category of problems that have the potential for being a logical and popular domain for application of expert system technology. Two systems have been presented that deal with diagnoses of problems and failures in environmental systems. The system developed by Huang et al. [2] is concerned with diagnosing failures in hazardous waste incineration facilities. Johnston [4] has developed a system with similar goals except that this system deals with a waste water treatment facility.

When the systems discussed are categorized according to the progra' .ing tool utilized, even more interesting conclusions can be drawn about the direction expert system technology is taking in these engineering areas. There are two general environments that can be used for developing knowledge-based expert systems, one is based on expert system shells that often can run on personal computers (PC) or small work stations, and the other being high level languages that are typically implemented on mainframe computers. The trend in engineering analysis and design in general has been towards decentralized computing that can be accomplished on personal computers and work stations whenever possible. This trend has been fueled by the great advances in computer technology and by the convenience and cost savings that personal computers can provide. It is not surprising then to see that many of the prototype systems discussed in this chapter have been developed using expert system shells on personal computers. Table 4-1 lists the systems presented in this chapter and their domain of interest. Almost half of the systems in this table are PC or workstation based. The fact that many systems are still based on mainframes reflects th^ relatively young age of expert system technology. As the techniques of expert systems mature it is likely that the trend towards personal computers will strengthen and fewer operation systems will be developed using high level languages on mainframes. With this trend towards PC based systems, an increase in accessibility of expert system technology will likely occur.

Ultimately, this new technology must be incorporated into the day-to-day engineering profession. To

accomplish this goal several issues have to be resolved. First the systems must be accessible, which is one factor that favors PC based systems. Secondly, the novice user must be able to consult the system with relative ease. The importance of this issue is reflected by the amount of research that is going on in making user interfaces more friendly by utilizing graphical input, for example. Another issue that can not be overlooked concerns the reliability and perceived accuracy that is associated with these systems. The only way to prove the value offered by expert systems is to build-up a history of successful applications to real engineering problems. The real success of this new technology should be measured by its level of acceptance in the engineering community and not solely by its value as a research tool.

Operational Systems

SYSTEM	DOMAIN	ENVIRONMENT
Geotechnical Engineering:		
CONE	Site Characterization and Shear Strength	OPS5
RETWALL	Retaining Walls	M.1*
Shallow Trench	soil classification and trench excavation	Personal Consultant*
SOILCON	subsurface risk	M.1*
Environmental Engineering:		
Hazardous Waste		
PVC Liner	Waste/Liner Compatibility	unreported
GEOTOX	Hazardous site evaluation	PROLOG
Waste Incineration	Waste incineration facility	M.1*
Inactive Waste Sites	Hazardous site evaluation	OPS5
DEMOTOX	groundwater contamination	M.1*
Waste Water Treatment		
Activated sludge	water treatment facility	microcomputer*
Water Resource Management		
FLOOD	Flood prediction	'C' language

(*) - denotes personal computer based environments

Table 4-1: Summary of Systems

References

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Chapter Five
Expert Systems in Transportation Engineering

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State-of-the-Art of Expert Systems
In Transportation Engineering

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1. Introduction

1.1 What is Transportation Engineering

Transportation engineering involves a wide spectrum of activities related to:

- o planning
- o design
- o operation and control
- o management
- o maintenance and rehabilitation

of multimodal facilities and services*. Such transportation facilities and services are needed for the safe and efficient movement of people and goods, and provide basic mobility as well as accessibility to workplaces, customers, schools, businesses, recreation and other social and economic opportunities vital to our standard of living and national economy. Transportation is therefore a derived demand, derived from the desire to pursue activities at a destination. Some of the basic components of transportation systems include vehicles and users, "links" (such as roadways, rail-lines, waterways etc.), "nodes" (such as intersections, interchanges, terminals etc.) and operating and control procedures and policies, as well as pricing and regulatory policies.

1.2 Reasons For Using Expert Systems in This Area

Computers are an essential tool for many of the activities listed in the previous section. In fact, many would be computationally intractable without computer models. However, it is also true that many tasks in transportation engineering lack explicit numerical algorithms, and are so complex or ill-defined that conventional computer tools are of limited use. Nevertheless, the tasks are addressed, and

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* construction of facilities is not included because a separate chapter is devoted to construction engineering and management.

problems solved, but using human judgement and experience. Expert systems have great potential for solving such ill-structured problems in the transportation field.

In recent years, expert systems have emerged from decades of research into artificial intelligence, which addresses problems traditionally thought to require human intelligence in order to find a solution, e.g. natural language processing, speech recognition, computer vision and robotics. Expert systems are designed to emulate the performance of an expert, or group of experts, in a particular problem domain. Such systems are primarily applicable to situations requiring specialized knowledge, skill, experience or judgement for determination of a solution, or development of a solution strategy. In such cases, the problem is usually said to be ill-structured, in the sense that a numerical algorithmic solution is not available or is impractical. The transportation field, in particular, is full of such ill-structured problems where human behavior, social and political considerations, and multi-objective decision-making are involved, Because so many of the problems that transportation professionals face are of this kind, (e.g. designing an optimal transit route network or making decisions about how to rehabilitate a deteriorated section of highway), it can be said that the potential is high for knowledge-based expert systems to become useful tools for the practicing transportation engineer. One can envisage such systems functioning as expert consultants, capable of explaining their reasoning and why they arrive at certain conclusions. Thus, one could eventually expect to learn from an expert system in the same way that one learns from a dialogue with a transportation engineering specialist or expert consultant.

The expert systems reviewed in this chapter are divided into two basic groups, operational prototype systems and systems under development. Further, the expert systems are categorized by their dominant functional application in transportation engineering, in either planning, design, operation and control, management or maintenance and rehabilitation. In some cases, of course, individual systems overlap several of these areas and this is noted in the Conclusions to the chapter.

2. Operational Expert Systems

2.1 Commercially Available or Used in Practice

Until recently, very little work on expert systems in transportation engineering had been reported in the literature. Currently, there are basically no systems known to be commercially available or used in transportation engineering practice. The systems that are operational or under development, as reported in this chapter, are prototypes that remain to be extensively tested in a user environment prior to possibly becoming commercial systems. An operational expert system that probably comes closest to fitting into the commercial category is DELTA, a system to help maintenance personnel diagnose and repair malfunctions in diesel electric locomotives. DELTA was developed by the General Electric Company at their research and development center in Schenectady, New York. However, because DELTA does not relate strongly to civil engineering aspects of transportation it will only be briefly described. The system can lead the user through an entire repair procedure, presenting computer-aided drawings of parts and subitems, repair sequences in the form of videodisc movies, and specific repair instructions once the malfunction is determined. DELTA is a rule-based system, originally developed in LISP, but later reimplemented in FORTH for installation on microprocessor-based system. Rules are accessed through both forward and backward chaining and certainty factors are used to handle uncertain rule premises. The system has been field-tested. This system is discussed in Waterman (1986), Bonissone and Johnson (1983), and DELTA/CATS-1 (1984).

2.2 Operational Prototypes

2.2.1 Planning

There are currently no systems in this category.

2.2.2 Design

2.2.2.1 CHINA

Introduction: CHINA is the Computerized Highway Noise Analyst, and addresses the problem of designing highway noise barriers. CHINA contains the expert knowledge of several specialists in the control of highway noise and can act as an expert advisor to the novice engineer or as a colleague to more experienced engineers on complex abatement problems.

Methodology: CHINA interacts with an existing FORTRAN model that aids the engineer in acoustically designing a highway noise barrier. CHINA executes the design model, interprets the results and decides if those results are valid. If they are not, CHINA determines new input parameters and re-executes the design model until a satisfactory design is obtained.

CHINA is a rule-based system and was developed in UCI LISP on a DEC system 1099 mainframe computer. It uses an inference engine called GENIE (General Inference Engine), which was developed by electrical engineers at Vanderbilt University to build expert systems in medicine and robotics. CHINA has been evaluated on several test cases designed to test the limits of its ability and produced barrier designs that were acceptably close to the design of human experts.

CHINA was developed in the Department of Civil and Environmental Engineering at Vanderbilt University as the Ph.D. dissertation of Dr. Al Harris, working with Professors Lou Cohn and Bill Bowlby. Continued development is now occurring at the University of Louisville, where Professors Harris and Cohn are with the Department of Civil Engineering.

References: Harris et al. (1985), Cohn et al. (1986), Harris et al. (1986).

2.2.2.2 TRALI

Introduction: TRALI is an expert system that provides assistance to traffic engineers designing traffic signal settings for isolated signalized intersections. This is a classic and common problem in transportation engineering. TRALI addresses a shortcoming of existing design aids which cannot deal with uncommon intersection geometries. TRALI was developed as an experimental prototype to explore the potential of expert systems, it is not a production level system suitable for field application.

Methodology: TRALI uses algorithmic processes to evaluate signal settings. Decision tables to identify traffic flow conflicts are invoked by the expert system, and phase distribution of flows is performed by applying heuristic rules. The main tasks used by TRALI in designing the operation of a traffic signal include: (1) conflict determination (2)proposal of a phase distribution (3) determination of the optimum cycle length and periods (4) calculation of figures of merit and (5) modifications to data and results. TRALI does not enumerate all possible solutions for a given intersection, but tries to mimic a search by a knowledgeable traffic engineer to follow a more direct procedure towards a good design alternative. Interactive analysis is repeated until the traffic engineer finds that a good solution has been identified.

TRALI was written in OPS5 for a VAX mainframe computer. It is a rule-based system with over 200 rules in the knowledge base. TRALI has a combined control strategy, involving both sequential execution and forward chaining. It currently does not incorporate uncertainty of rules or data, or multiple design criteria, although future extensions such as this are possible.

TRALI was developed by Mr. Carlos Zozaya-Gorostiza and Professor Chris Hendrickson in the Department of Civil Engineering at Carnegie-Mellon University.

Reference: Zozaya-Gorostiza and Hendrickson (1986).

2.2.2.3 EXPERT UFOS

Introduction: EXPERT-UFOS is an expert system for large-scale transportation network design problems that are evaluated using multiple conflicting criteria. More specifically, the system addresses the design of single-mode (automobile), fixed-demand, discrete, equilibrium transportation networks. Previous attempts to solve this class of problem involved mathematical programs that, it is claimed, only performed well on small networks and using only one objective.

Methodology: EXPERT-UFOS resulted from a research study that was limited to the problem of designing an optimal network by adding or deleting capacity from any link in the network. With 5 capacity settings, the number of possible solutions is 5^n, where n is the number of links in the network. The design problem involves finding a set of capacity additions and deletions that will improve the overall performance of each design relative to the previous design as much as possible. A concordance analysis multicriteria evaluation method was integrated into the expert system, and used criteria of cost, congestion and average travel time to evaluate each design. Performance measures for each design were derived from a computationally intensive equilibrium traffic assignment model; therefore, the fewer design cycles the better. The resulting EXPERT-UFOS systems is an almost totally automated design machine, requiring little assistance from the human operator. The knowledge base was constructed by studying the successful design strategies of 76 student designs resulting from a four week test case example (no existing human or written expertise was available). EXPERT-UFOS was said to result in better solutions than were found by the students in the test case.

EXPERT-UFOS was developed on an IBM-AT microcomputer using the M.1 rule-based, backward chaining development tool by Teknowledge. The system was part of a doctoral dissertation by Dr. Shieng-I Tung in the Department of Civil Engineering at the University of Washington.

Reference: Tung (1986).

2.2.3 Operation and Control

2.2.3.1 HERCULES

Introduction: HERCULES is an expert systems approach to generating a traffic control plan that, if implemented, would make good use of the links remaining in a post-disaster urban road network. While most urban networks are quite congested during peak-periods under normal operating conditions, a natural or human-made disaster of major proportions would cause much worse post-disaster congestion problems. One could expect various bridges, freeway interchanges and

links, tunnels and other segments of the transportation network to be damaged, perhaps for a long period of time. Means of keeping post-disaster congestion at tolerable levels therefore need to be developed beforehand so that they can be implemented quickly under post-disaster conditions.

Methodology: The knowledge base for HERCULES was derived from the results of a specially developed network simulation model. This involved identifying key links and forbidden links for each origin-destination pair in the broken network. HERCULES recommends traffic control plans that limit the allowable volumes on the remaining links in the network. This necessarily involves keeping some traffic off the network, and also greater use of high occupancy vehicles such as car pools and buses. In several test cases, HERCULES control plans have been found to yield significant improvements in five areawide performance criteria compared with the do-nothing case. The advice obtained from HERCULES is more extensive and comprehensive than could be expected from a human expert but provides no guidance on how to implement the control plans. Also, the knowledge base is currently very specific to each network.

HERCULES was developed in CLisp on a VAX 11/780 mainframe computer. It is a rule-based forward chaining system, and was developed as part of a doctoral dissertation by Dr. Che-I Yeh in the Department of Civil Engineering at the University of Washington.

Reference: Yeh (1985).

2.2.4 Management

There are currently no systems in this category.

2.2.5 Maintenance and Rehabilitation

2.2.5.1 SCEPTRE

Introduction: SCEPTRE is the Surface Condition Expert for Pavement Rehabilitation. It is a major component of PARADIGM (see section 3.2.5.1), an integrated set of expert systems now under development for analysis and design of pavement rehabilitation strategies. SCEPTRE is intended to be an expert pavement engineering advisor and even instructor for other engineers, particularly in local agencies at the city and county level. Such engineers typically do not have the training, experience, time or even data to make optimal pavement rehabilitation decisions. In fact, successful strategies are usually developed by a relatively small number of pavement engineering specialists, to be found in some state and federal agencies, universities, and private firms, but generally not in local agencies. However, about 75% of the nation's highway mileage is the responsibility of these local agencies. Their needs are therefore enormous, not only financially but in

terms of human resources and expertise. Expert systems have the potential to play a very significant role in addressing these problems.

Methodology: SCEPTRE basically evaluates project level pavement surface distress and other user inputs to recommend feasible *rehabilitation* strategies for subsequent detailed analysis and design (for example, by OVERDRIVE; see section 3.2.5.1). SCEPTRE has been developed using the knowledge engineering shell EXSYS on a Compaq portable microcomputer (and runs on any MS-DOS compatible PC). The system is rule-based and uses a backward chaining inference method. The knowledge base in version 1.4 contains about 140 complex rules, derived from the combined expertise of two pavement specialists. SCEPTRE 1.4 addresses state-maintained flexible pavements in Washington State, and is beginning field testing in District Offices of the Washington State Department of Transportation (WSDOT). On-going research will refine and adopt the knowledge base for local agencies. SCEPTRE is being developed by Professor Stephen G. Ritchie and Dr. Che-I Yeh in the Department of Civil Engineering and Institute of Transportation Studies, University of California, Irvine, and with colleagues at the University of Washington and Washington State Department of Transportation.

References: Ritchie (1986), Ritchie et al. (1986a), Ritchie et al. (1986b).

3. Expert Systems Under Development

3.1 Demonstration Prototypes

The following systems are currently in relatively early stages of development. They have reached the stage of a working prototype expert system that may address a portion of the problem undertaken, suggesting that further development is viable. These systems have generally not been substantially validated or refined.

3.1.1 Planning

There are currently no systems in this category.

3.1.2 Design

3.1.2.1 Forest Road Design

Introduction: An expert system for developing the layout of forest roads has been developed at Purdue University, for ultimate use by National Forest Service engineers. Because road layout is difficult to do in purely quantitative terms, the system uses heuristics to attempt to optimize parameters describing the layout.

Methodology: The system starts with critical points on the surface and then tries to fit a solution through those points. The system can give design advice on roadway spacing based on the terrain, soil type and equipment availability.

The system has been programmed in LISP (UNIX system) for a mainframe computer; the use of a PC-based expert systems development shell such as Insight 2+ is also being investigated. The inference method used is forward chaining.

This system has been developed by Professor Jon Fricker in the Department of Civil Engineering at Purdue University.

Reference: Personal communication with Professor Fricker.

3.1.3 Operation and Control

There are currently no systems in this category.

3.1.4 Management

3.1.4.1 DIRECTOR

Introduction: DIRECTOR is an expert system that was designed to be an intelligent advisor to users of the "Streets of the City" simulation model, and to primarily serve as an educational tool for transportation engineering students. "Streets of the City" simulates the decision-making activities of a Transportation Director in a medium-sized, declining mid-Western city. The person operating the simulation tries to achieve street and transit system goals set by the city commissioners, over a 10 year period. If yearly performance is unsatisfactory, the Director is fired and the simulation stopped. The simulation is complex and requires the user to relate to multi-objective decision-making involving ill-defined trade-offs. Most novice users of the simulation get fired early in the 10 year period, but gradually become "expert" and improve their performance. DIRECTOR was developed to investigate whether this performance improvement could be enhanced through an expert advisor.

Methodology: The knowledge-base of DIRECTOR consists of two different levels:

(1) A semantic network with each node of the network representing one item in the simulation; for example, Transit Maintenance Budget, Traffic Safety Index, and Transit Fare. The links of the network describe the relationships among the nodes. For example, some relationships are: bus fleet age affects bus downtime, bus downtime affects the service delay index and service delay index affects ridership. The DIRECTOR knowledge-base consists of 30 nodes and 100 links in its basic network structure.

(2) Rules for inferring the solution strategies. These rules work first on the "weak spots" among the performance measures and the elements that cause the weak performance. Then a suggested decision is identified based on the information at hand. This advice is presented to the user, who can accept it, in whole or in part, as an input to the following year's budget formulation process.

DIRECTOR was implemented in CLisp on a VAX 11/780 mainframe computer. The inference mechanism uses a forward chaining search procedure. The system provides limited explanation for specific questions related to information included in the semantic network. DIRECTOR's performance was not throughly evaluated but in limited tests achieved levels very few unassisted users could attain.

DIRECTOR was developed by Dr. Che-I Yeh in the Department of Civil Engineering at the University of Washington. There has been no further development of the system since 1984, although Drs. Yeh and Ritchie, at the University of California, Irvine, intend to resume working on it.

Reference: Personal communication with Dr. Yeh, Institute of Transportation Studies, University of California, Irvine.

3.1.5 Maintenance and Rehabilitation

3.1.5.1 PRESERVER

Introduction: PRESERVER is an expert system that is being developed to advise field engineers and maintenance foreman on recommended road maintenance strategies. The system is conceptually similar to SCEPTRE (see Sections 2.2.5.1), but focuses on routine maintenance activities whereas SCEPTRE currently emphasizes more major rehabilitation strategies. Both systems now address state or provincially-maintained highways, although SCEPTRE is being developed as a tool for highway engineers in local city and county agencies.

Methodology: PRESERVER incorporates maintenance treatment actions designed for Ontario road conditions. The system includes rules for a subset of distress types defined in a Pavement Maintenance Guidelines Manual of the Ontario Ministry of Transportation and Communications. This manual was a principal knowledge source. Based on observed distress information provided to PRESERVER by the user, sets of feasible treatments for each distress condition are generated. If there is more than one distress condition, PRESERVER selects a feasible set of treatments based on the original sets generated.

Complete implementation of a PRESERVER prototype would require quite a few additional rules. The existing system has been used to illustrate and test concepts. It has been developed in OPS5 for a VAX mainframe computer and is a rule-based system. The main sections of the program are sequential, with subsections said to utilize both forward and backward chaining inference methods.

PRESERVER is being developed by Mr. Carl Haas in the Department of Civil Engineering at Carnegie-Mellon University.

References: Personal communication with Mr. Haas, and Haas (1986).

3.2 Conceptual Prototypes

The following systems are at the conceptual stage of development. They represent conceptual or preliminary designs for systems, prior to the existence of a working prototype.

3.2.1 Planning

There are currently no systems in this category.

3.2.2 Design

3.2.2.1 Pavement Test Section Evaluation

Introduction: An expert system is planned at Purdue University to improve evaluation of pavement test sections that were built to establish design criteria. The system is directed toward the agencies building these test sections eg., Department of Defense and Department of Transportation.

Methodology: An expert systems approach is proposed because the overall problem is very complex, and involves several phenomena. It takes a very experienced materials or pavement engineer to look at all the phenomena and decipher pavement performance. It is felt that an expert system could consider a greater number of phenomena and achieve more accurate prediction of pavement section performance, thereby resulting in improved design criteria and actual pavement designs.

The hardware and software development environment for the expert system has not yet been determined, although free student use of a network of some 23 VAX computers at Purdue is available. The system is being developed by Professor T.D. White in the Department of Civil Engineering at Purdue University.

Reference: Personal communication with Professor White.

3.2.3 Operation and Control

3.2.3.1 Air Traffic Control

Introduction: The application of expert systems in air traffic control is being studied at the University of California, Berkeley. The air traffic control (ATC) system in the United States is currently facing the need to handle ever increasing volumes of air traffic, without corresponding increases in the size of the controller force. Apart from the high costs that would be associated with such an expansion, there are technical limits to the minimum size of an airspace sector under the control of one person. As sectors approach this minimum practical size, it becomes progressively more difficult to handle increasing traffic volumes by adding personnel. However, maintaining sector sizes in the face of growing traffic leads to unacceptable levels of controller workload.

Methodology: Among the alternative techniques that exist to support advanced automation features, expert systems appear to offer a wide range of potential applications. In particular, expert systems approaches are proposed for traffic flow management, controller support functions, system failure management, training, and system configuration planning. Special requirements have to be considered in the design of a real-time control expert system. To explore how these might be addressed, initial efforts involve developing a prototype expert system to assist in air traffic flow management. The objective of the system is to assign appropriate flight departure delays to a sequence of scheduled arrivals at a capacity-constrained airport. Initial delay allocation rules have been developed.

This system is being developed by Professor Geoff Gosling in the Department of Civil Engineering at the University of California, Berkeley.

Reference: Gosling (1986).

3.2.3.2 Disaster Response

Introduction: The focus of this research is the integration of human expert knowledge and algorithmic techniques for the optimal routing and scheduling of emergency vehicles after a major disaster. The integration of heuristics and algorithmic knowledge is felt to be the key to fully exploiting the potential of both expert systems and mathematical programming approaches in this domain. The efficient use of ambulance and paramedic vehicles is essential for saving lives and reducing the severity of injuries in a disaster situation.

Methodology: In a major earthquake disaster, the road network could be severely impaired due to broken or damaged links, and bridge and overpass structural failures. Thus, information regarding serviceable routes for emergency vehicles would have to be continually updated. Such updating could be one important task of the expert system. A second consideration is that in a major disaster, communications may be disrupted. The expert system could assist in making inferences with incomplete or uncertain information. Also, emergency personnel may themselves be injured and thus unable to assist others. A key feature of an expert system is the ability to preserve the knowledge of experts. In this manner, inexperienced personnel can assist in the coordination of emergency response resources if experts are unavailable. Finally, with the possibility of inadequate vehicles, equipment, and personnel, the expert system must be capable of prioritizing responses to calls, selecting appropriate response teams, and matching victims and possible care facilities.

The principle aim of this expert system is to advise on the assignment of routes to emergency vehicles and tasks to emergency teams. The optimal allocation of emergency response vehicles and teams in this situation can be viewed as a large-scale vehicle routing and scheduling problem. Mathematical programming-based algorithms can be used to solve these problems, either exactly or approximately. Here, the expert system and the mathematical program can aid each other. The expert system assists the mathematical program by quantifying and updating various inputs while the mathematical program provides the expert system with a means of selecting from among a large number of alternative resource allocation decisions. Initially, one or more key components of this system will be implemented in an experimental system for a small case study network. The system is expected to be developed in LISP on a PC or on a more powerful workstation.

The system is being developed at the University of California, Irvine, by Professor Stephen Ritchie, Department of Civil Engineering, and Professor Bruce Lamar, Graduate School of Management, through the Institute of Transportation Studies, Irvine.

References: Personal communication with Professors Lamar and Ritchie.

3.2.3.3 Work Zone Traffic Control

Introduction: Consideration is being given to design of an expert system for managing traffic flow through road construction work zones. The system could be used by district engineers in a state highway department as a means of considering all available options.

Methodology: This system is at such an early stage of development that no further information is available. It is being developed by Professor Michael Demetsky at the University of Virginia.

Reference: Personal communication with Professor Demetsky.

3.2.4 Management

There are currently no systems in this category.

3.2.5 Maintenance and Rehabilitation

3.2.5.1 PARADIGM

Introduction: PARADIGM represents the Pavement Rehabilitation Analysis and Design Mentor, a proposed integrated set of expert systems for local highway agencies. PARADIGM is the focus of ongoing research at the University of California, Irvine, and also involves colleagues at the University of Washington, and Washington State Department of Transportation (WSDOT). The system is microcomputer-based.

Methodology: As presently conceived, PARADIGM consists of at least four integrated component expert systems:

(1) SCEPTRE (Surface Condition Expert for Pavement Rehabilitation) - to identify project-level feasible pavement rehabilitation and maintenance strategies (RAMs) for bituminous pavements, based on expert evaluation of pavement surface condition. SCEPTRE is described in Sections 2.2.5.1 and 2.3.

(2) OVERDRIVE (Overlay-Design Heuristic Adviser) - to provide interactive expert advice and guidance for the detailed design of project-level asphalt concrete overlay rehabilitation strategies. This system is under development. The initial system is rule-based and employs a forward chaining inference method. It is being implemented in muLISP on a Compaq microcomputer.

(3) Two similar systems for utilizing project-level information generated by either SCEPTRE or OVERDRIVE that would derive an optimized network-level rehabilitation plan, subject to construction budget constraints. Essentially, these two systems would be intelligent pre- and post-processors for an integer programming formulation that would determine the most cost-

effective rehabilitation and maintenance strategies or detailed designs subject to various constraints of an economic, engineering, political, administrative or geographic nature. The pre-and post-processor would offer intelligent advice and a more user-friendly environment for those users less familiar with optimization techniques to formulate the problem and its constraints, and then to interpret the optimal solution and its characteristics. The ability to achieve this close coupling of subjective heuristic knowledge and algorithmic procedure is of considerable interest in engineering applications of expert systems generally.

PARADIGM is being developed under the direction of Professor Stephen Ritchie, Department of Civil Engineering and Institute of Transportation Studies, University of California, Irvine.

Reference: Ritchie (1986).

3.2.5.2 Pavement Rehabilitation

Introduction: Another expert system in the pavement rehabilitation area is being proposed by the Quebec Ministry of Transportation, Canada.

Methodology: This system would be microcomputer-based and use the EXSYS knowledge engineering tool. The system will therefore be rule-based and employ backward chaining (although the new version of EXSYS, version 3.1, now includes forward-chaining as well). Initially, the system will be modeled after SCEPTRE (see Section 2.2.5.1).

Reference: Personal communication with Mr. Mario Beland, Direction of Research, Quebec Ministry of Transportation, Canada.

3.2.5.3 Bridge Replacement

Introduction: An expert system is proposed at the University of West Virginia to assist county bridge engineers determine the kinds of low-volume bridges that may need to be replaced. Existing approaches are said to be intuitive.

Methodology: The system would be rule-based and use the microcomputer shell EXSYS (see above). It is hoped to have a working prototype in about a year. Because this system is at such an initial stage, no more information is available. The system is being developed by Professor Hota GangaRao in the Department of Civil Engineering, University of West Virginia.

Reference: Personal Communication with Professor GangaRao.

4. Conclusions

Because so many of the problems transportation professionals face require specialized knowledge, skill, experience and judgement for determination of solution strategies, in general the potential appears high for expert systems to become a useful tool for practicing transportation engineers. This state-of-of-the-art review of expert systems in transportation engineering reflects the fact that comparatively little work on expert systems in the transportation field has been reported to date. However, considerable research is underway and can be expected to grow. New operational systems will follow. A review of current operational prototype systems as well as systems under development was presented in this chapter in the areas of planning, design, operation and control, management and maintenance and rehabilitation.

A summary of operational prototype expert systems is presented in Table 1. It is interesting to note that the majority of these applications have been in the design area, with none of the five systems having a primary focus in planning, or management, functional areas. Table 2 presents a summary of expert systems under development. Again, the focus of developments to date has been in the areas of design, operation and control, and maintenance and rehabilitation (with a much larger proportion in this last category than for current operational prototypes).

It is also interesting that, as far as is known, the hardware/software environments for all the efforts in Tables 1 and 2 have involved "conventional" machines, from microcomputers to mainframes, and software including PC shells (such as EXSYS, INSIGHT, and M.1), OPS5 and LISP. To date, there has been no work reporting use of dedicated symbolic processing machines nor "high-end" expert system development tools. This is not surprising given the early stage of research into expert systems in transportation engineering, the relatively low level of research funding in transportation engineering, and the dual resource constraints facing academic researchers and potential end-users, many of the latter being in budget-constrainted public agencies. Furthermore, many potential end-users in fact prefer and demand PC-based tools, and researchers are sensitive to this fact. Because expert systems could revolutionize professional activities in many areas of transportation engineering, further research, and an improved level of research funding, is essential.

Finally, the breadth of the transportation field is such that there are numerous problems yet to be addressed that also represent high-potential applications of expert systems. To identify new applications and research needs, consultations with appropriate experts are required, together with a more careful and complete review of domain-dependent problems. Such work is now underway and will be followed by the development and evaluation of new prototype expert systems. This will continue to improve our ability to assess the feasibility and utility of expert systems in transportation engineering.

Section	Expert System	Planning	Design	Operation and Control	Management	Maintenance and Rehabilitation
2.2.2.1	CHINA		X			
2.2.2.2	TRALI		X	(X)		
2.2.2.3	EXPERT-UFOS	(X)	X			
2.2.3.1	HERCULES	(X)		X		
2.2.5.1	SCEPTRE				(X)	X

Note:

X indicating primary functional area in transportation engineering.
(X) indicating secondary functional area(s) in transportation engineering.

Table 1. Classification of Operational Prototype Expert Systems

Section	Expert System	Planning	Design	Operation and Control	Management	Maintenance and Rehabilitation
	Demonstration <u>Prototypes</u>					
3.1.2.1	Forest road design		X			
3.1.4.1	DIRECTOR	(X)			X	
3.1.5.1	PRESERVER				(X)	X
	Conceptual <u>Prototypes</u>					
3.2.2.1	Pavement evaluation		X			
3.2.3.1	Air traffic control			X		
3.2.3.2	Work zone traffic control			X		
3.2.3.3	Disaster response	(X)		X		
3.2.5.1	PARADIGM		(X)		(X)	X
3.2.5.2	Pavement					X
3.2.5.3	Bridge replacement					X

<u>Note</u>:

X indicating primary functional area in transportation engineering.
(X) indicating secondary functional area(s) in transportation engineering.

Table 2. Classification of Expert Systems Under Development

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